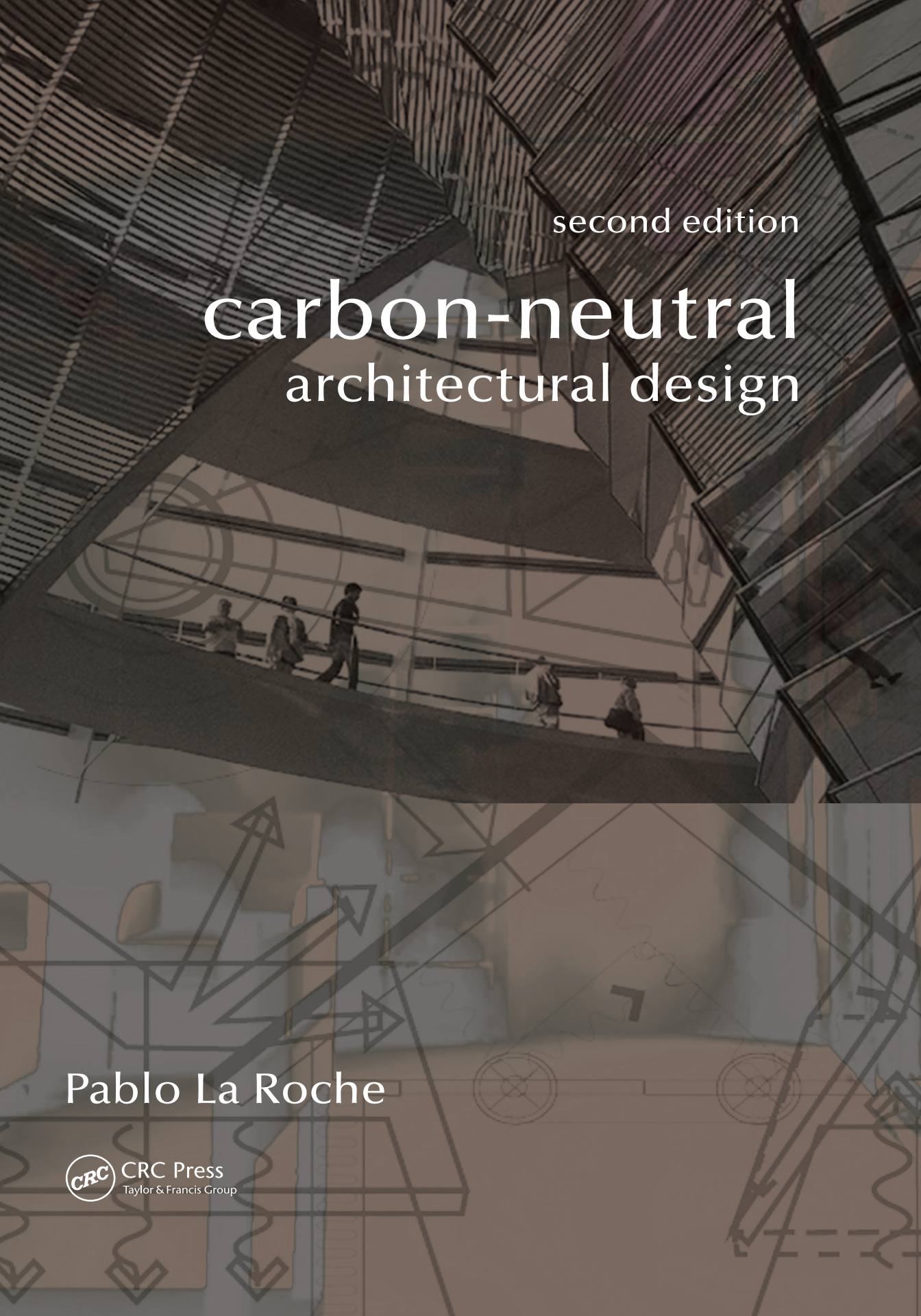

second edition

carbon-neutral architectural design

Pablo La Roche

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Carbon-Neutral Architectural Design

Second Edition

by

Pablo La Roche

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Foreword

This book recognizes that energy efficiency and passive/low-energy design are the fundamental components of buildings that aim for high performance. A truly high-performance building does not add to the sum of carbon in our atmosphere, starting with construction, continuing through a lifetime of occupancy, and ultimately with the building's demise. Obviously, a highly ambitious goal!

This new edition deals more thoroughly with global climate changes that necessitate carbon-neutral design. There are many more and new examples of student work and new examples from professional practice. They show how building form results by applying the principles of heating, cooling, and lighting to achieve comfort. The book ends with a new section on performance simulation.

The scope of this book is summarized in a matrix. From the widest regional scale to the smallest building component, the carbon-neutral goals include the stages of building construction, operation, water, and waste. This is presented in stages from the earliest exposure to beginning designers through those designers who are more advanced.

The students and designers who pursue this process will first be shown the fundamentals that underlay daylighting, passive heating, and passive cooling. The author has taken this basic approach rather than present shortcut "design guidelines" more common in the textbooks in this field. This is demanding but also an invitation to think for one's self about new approaches to these rather old subjects. In his words, "It requires a new set of skills and a transformation in how we think about buildings and how we design and produce them." He illustrates this with several experiments and projects developed at the University of California, Los Angeles, (UCLA), Los Angeles, California and Cal Poly Pomona, Pomona, California. My favorite among these is a continuing project, "the Tijuana Low Cost Sustainable Housing Prototype," in which many low-cost sustainable systems are tested by Cal Poly Pomona students.

The author's approach to carbon-neutral building design builds on his work with his two most important mentors: Baruch Givoni and Murray Milne. The work of these UCLA architectural science educators is legendary. The design community is rich with those who have studied with them, and our cities are fortunate to have the buildings that have benefitted from their work.

Currently, among energy-conscious architects and engineers, we see an emphasis on building equipment rather than the building envelope. Too many designers (and design incentive programs) are content with an array of photovoltaic (PV) panels on a roof rather than careful building orientation, window shading in summer, low-glare daylighting, and solar gain to help with winter heating in addition to PV that is integrated in the façade or roof. This book is a challenge to go deeper, to better understand not only how to achieve truly high performance but why.

John S. Reynolds
University of Oregon

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Preface

Energy used to operate buildings is one of the most significant sources of greenhouse gases (GHG) to the atmosphere, making it impossible to achieve the necessary reductions in anthropogenic emissions without implementing significant reductions in building sector emissions. Even though this can be done using current technologies, it requires a new set of skills and a transformation in how we think about buildings and how we design and produce them. This book provides an introduction to the basic concepts necessary for the design of low-emission and carbon-neutral buildings, an important part of any coherent set of measures to reduce anthropogenic emissions and our impact on climate change. I propose and discuss a method to reduce building emissions with an emphasis on the development of an envelope that works seamlessly with the Heating, Ventilation and Air Conditioning (HVAC) system, providing carbon-free heating, cooling, and daylighting whenever possible. This method is dynamic and can be adapted and further customized by the user, including different strategies as appropriate.

Increased awareness has made the reduction of building emissions a priority for many around the world. In the United States, some organizations have taken important steps to push this cause. Notable ones include 2030 Architecture led by Ed Mazria, the American Institute of Architecture (AIA), an early adopter of the 2030 challenge through its 2030 commitment, the American Solar Energy Society (ASES), and the American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE). Many similar organizations have done the same all over the world. However, this is not enough. Climate change is accelerating, and 2016 has blown away temperature records. Reducing anthropogenic emissions is more critical than ever. My hope is that this book will contribute to achieve the carbon-neutral buildings that we need today.

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I am grateful to the Society of Building Science Educators' Carbon Neutral Design Project and especially to Jim Wasley and Terri M. Boake for providing me an opportunity, through my participation in this project, to organize some of my initial ideas for the first edition.

I am also grateful to Energy Design Resources, funded by California utility customers and administered by the Pacific Gas and Electric Company, Sacramento Municipal Utility District, San Diego Gas and Electric, Southern California Edison, and Southern California Gas under the auspices of the California Public Utilities Commission, and especially Diane MacLaine and Judie Porter for supporting me in the initial phases of the first edition of this book.

I also thank the many students of the department of architecture and the Lyle Center for Regenerative Studies at Cal Poly Pomona University, California, who have in some way been involved with this book. They always inspire and motivate me to work harder. I would also like to thank Kyle Brown, director of the Lyle Center, and the rest of the center's staff for supporting some of my research, which is included in this book.

I am also grateful to Baruch Givoni and Murray Milne. I was fortunate to have them both as my PhD advisors at the University of California, Los Angeles, California.

I am always grateful to my parents for providing me with a good education and a social conscience, with the spirit to work hard to achieve my goals and become a better person.

Finally, I thank my wife, daughters, and son for supporting me and giving me the time to work on this project. I hope I will be able to repay them sometime.

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Author

Pablo La Roche is professor of architecture at California State Polytechnic University and Associate Vice President & Sustainable Design Leader at CallisonRTKL. Dr. La Roche has more than 25 years of experience in professional practice, implementing sustainable, low carbon strategies in multiple projects of all sizes. La Roche earned an architecture and a Master's of Science degree at Universidad del Zulia, Venezuela and a PhD degree at the University of California, Los Angeles, California. His research interests include passive cooling systems, green roofs, low-energy, and low carbon architecture, having published more than 130 papers on these topics in several conferences and journals. He has been a guest lecturer around the world, a member of architecture competition juries, and a technical reviewer and session chair in local, regional, and international events and conferences, such as the American Institute of Architecture (AIA), the Passive and Low Energy Architecture Association (PLEA), Architectural Research Centers Consortium (ARCC), U.S. Green Building Council (USGBC), and American Solar Energy Society (ASES) conferences. In 2016 he chaired the Passive Low Energy Architecture PLEA conference in Los Angeles. He is also past president of the Society of Building Science Educators (SBSE) and past chair of the solar buildings division of the American Solar Energy Society (ASES).

La Roche co-authored the book, *Keeping Cool: Guidelines to Avoid Overheating in Buildings*, published by PLEA in 2001, and authored *Carbon Neutral Architectural Design* in December 2011. He is a registered architect in Venezuela, and an associate AIA and Leadership in Energy and Environmental Design (LEED) BD+C accredited professional in the United States. He has received multiple awards and fellowships and his design projects have been published or received awards in the United States, Venezuela, Mexico, and Spain. Among these are the Volunteer IMPACT Award from the USGBC and the EDUCATE Prize in 2012, the National Council of Architectural Registration Boards (NCARB) Grand Prize for the department of Architecture at Cal Poly Pomona in 2008 and the exhibit "New Blood: Next Gen" in the A+D Architectural Museum in Los Angeles, California in 2006 and USGBC). His students have also received awards in many architecture competitions over the years.

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Introduction

This second edition of *Carbon-Neutral Architectural Design* is divided into 11 chapters, expanded from the original 8 chapters. Chapter 1 provides a brief introduction to climate change and its relationship with the built environment. The origins of different types of building emissions, as well as how these are generated through interactions between the buildings and the environment around them, are discussed. These interactions are affected by the building fabric and materials and building inputs and outputs (energy, construction, water, waste). The chapter ends with a comparison of several simple and free carbon-counting tools for residential building design.

A carbon-neutral architectural design process (CNDP) is proposed in Chapter 2, illustrated with diagrams that can be adjusted for different types of projects and including the types of emissions previously discussed: operation, construction, water, and waste. This process has been implemented in architectural education, discussed in Chapter 3, and in practice, discussed in Chapter 4, which also describes social sustainability.

Carbon-neutral buildings must achieve thermal comfort with a minimum amount of GHG emissions. Psychrometrics, thermal comfort, the variables that affect it, and different comfort models are discussed in Chapter 5, now including examples of the implementation of comfort strategies in outdoor spaces.

Chapter 6 is about understanding the climate where the building is located to identify appropriate climate responsive design strategies. Solar geometry is especially important because of the sun's potential to provide energy to the building or the need to block solar radiation when there is potential for overheating. Solar geometry is discussed in Chapter 7.

It is important to understand how energy moves through the building envelope. The heat balance equation is used in Chapter 8 to explain how the building fabric can be used to control energy flows by conduction, radiation, and convection, which would help to reduce summer overheating and winter underheating. Designing a good envelope that controls heat gains or losses is a necessary precondition to the implementation of passive heating and cooling strategies or mechanical heating and cooling systems.

A passive solar system utilizes the building fabric and materials to heat or cool the building. Passive heating and cooling systems are an important part of any carbon reduction process. Passive cooling systems can transfer heat from a building to various heat sinks and are classified according to the heat sinks that are used. Passive cooling systems are discussed in Chapter 9. Passive heating systems capture solar energy and then store and distribute it inside the space as needed. Passive heating systems are discussed in Chapter 10.

Energy simulations are important to achieve high-performing, low-carbon buildings, but simulations are often seen as difficult, expensive, and time consuming. Even though it is true that some simulations are sophisticated and require advanced training, there are some that can—and should—be undertaken by designers. Chapter 11 is a new chapter that introduces, with examples, some basic concepts in building simulation.

Many of the ideas discussed in this book had their origin in my research, teaching, or practice. I believe that practice research and teaching enrich each other. I am also a strong believer in the integration of design activities in traditional lecture courses and technical analysis in design studios. I have also tried to emphasize the implementation of design strategies to reduce energy consumption over mechanical systems whenever possible. Even though it is important that students understand how mechanical systems work, it is even more important that they learn how to design buildings that reduce the heating and cooling loads through design strategies and non mechanical systems, thus reducing building emissions.

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1 Buildings and Climate Change

1.1 THE GREENHOUSE EFFECT

The greenhouse effect occurs when radiation from the sun passes through the atmosphere and hits the surface of the Earth, which then absorbs it, heats up, and emits infrared radiation. Greenhouse gases (GHGs) in the atmosphere absorb most of this infrared radiation and then radiate in the infrared range, which is emitted upward and downward, with part of it absorbed by other atmospheric gases further raising their temperature, part of it escaping to space, and another part reflected downward toward the Earth's surface (Figure 1.1). The surface and lower atmosphere are warmed by the part of the energy that is radiated downward, making our life on the Earth possible. Without the greenhouse effect, the Earth's temperature would be too cold for life to exist.

Some GHGs occur naturally and are discharged to the atmosphere through natural processes and human activities, whereas other GHGs are created and emitted only through human activities. The main GHGs that enter the atmosphere as a product of human activities are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydroflourocarbon gases, and sulfur hexafluoride.

Most of the carbon dioxide that enters the atmosphere is a result of the burning of fossil fuels (oil, natural gas, and coal), solid waste, trees, and wood products, and other chemical reactions (e.g., manufacture of cement). Carbon dioxide is removed from the atmosphere, or "sequestered," when it is absorbed by plants as part of the biological carbon cycle. Methane is given off during the production and transport of coal, natural gas, and oil, from livestock and other agricultural practices, and by the decay of organic waste in municipal solid waste landfills. Nitrous oxide is emitted during agricultural and industrial activities as well as during the combustion of fossil fuels and solid waste. Fluorinated gases such as hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride are synthetic gases that are generated from a variety of industrial processes and sometimes used as substitutes for ozone-depleting substances. Water vapor is not a man-made GHG and is usually not considered a cause of man-made global warming because it does not persist in the atmosphere for more than a few days.

The concept of global warming potential (GWP) describes in one number the different capacities to affect climate change. The GWP is defined as the warming influence over a set time period of a gas relative to that of carbon dioxide, which under the Kyoto protocol is a 100-year time period. The GWP of the gases previously described is indicated in Table 1.1. Even though other gases have a much higher GWP, CO_2 is the most prevalent GHG and is the most commonly mentioned, sometimes inappropriately.

Another unit used to measure the impact of these gases in one single standard unit is the carbon dioxide equivalent (CO_2e), which also rates these gases based on their 100-year GWP, providing a way to compare emissions from different sources using a common unit of measurement (1 kg CO_2e = 1 kg CO_2). The standard unit is $MtCO_2e$ or metric tons of carbon dioxide equivalent. The global warming impact of all GHGs is measured in terms of equivalency to the impact of carbon dioxide (CO_2) via GWPs. The United Nations Environment Programme (UNEP) proposes CO_2e as the common carbon metric for international use in the gathering of data and reporting of the climate performance of existing buildings to (1) support policies under development to reduce GHG emissions from buildings, (2) provide a framework to measure emission reductions in buildings, and (3) establish a system with measurable reportable and verifiable indicators (UNEP SBCI, 2010). CO_2e is the unit of GHG measurement used throughout this book.

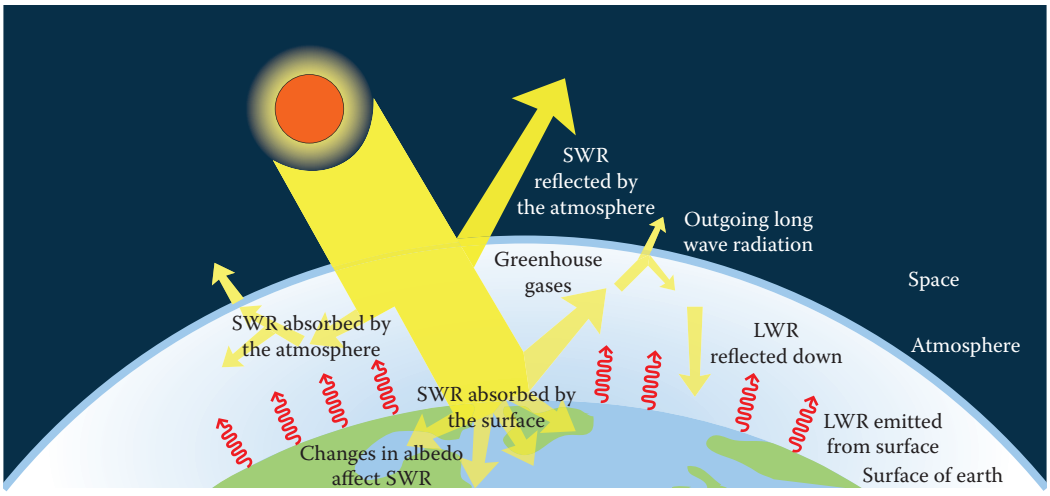


FIGURE 1.1 The greenhouse effect.

TABLE 1.1
GWPs of Several Common Anthropogenic GHGs

Greenhouse Gas	GWP
Carbon dioxide (CO_2)	1
Methane (CH_4)	21
Nitrous oxide (N_2O)	310
Hydrofluorocarbon gases	6,500
Sulfur hexafluoride	23,900

A global assessment of data since 1970 has demonstrated that "it is likely that anthropogenic warming has had a discernible influence on many physical and biological systems" (IPCC, 2007; Parry et al. 2007). Average global surface temperatures have increased by 0.74°C over the past 100 years, and much of the observed rise in sea level (12–22 cm) during the twentieth century is probably related to this increase in global mean temperatures.

1.2 EFFECTS OF ANTHROPOGENIC EMISSIONS ON CLIMATE CHANGE

Life on the Earth would not be possible if not for the greenhouse effect; however, an increase in the concentration of anthropogenic GHGs, especially CO_2, is affecting climate. The current Intergovernmental Panel on Climate Change (IPCC) climate models also predict that global temperatures will rise by an additional 1.1°C–6.4°C by the end of the twenty-first century, depending on the amount of emissions and how the different variables interrelate as climate changes over time. Global mean sea levels are also predicted to rise by 20–60 cm by 2100. Sea-level rise threatens coastal communities, whereas higher temperatures, drought, and flooding will affect people's health and way of life, causing the irreversible loss of many species of plants and animals. There is no doubt that climate change is the most serious environmental threat facing the planet. Along with warming at the Earth's surface, more extreme weather events are becoming more common. Heat waves have become more frequent and are lasting longer. The height of extreme sea levels caused by storms has increased. Warming is expected to cause more intense, heavy rainfall events.

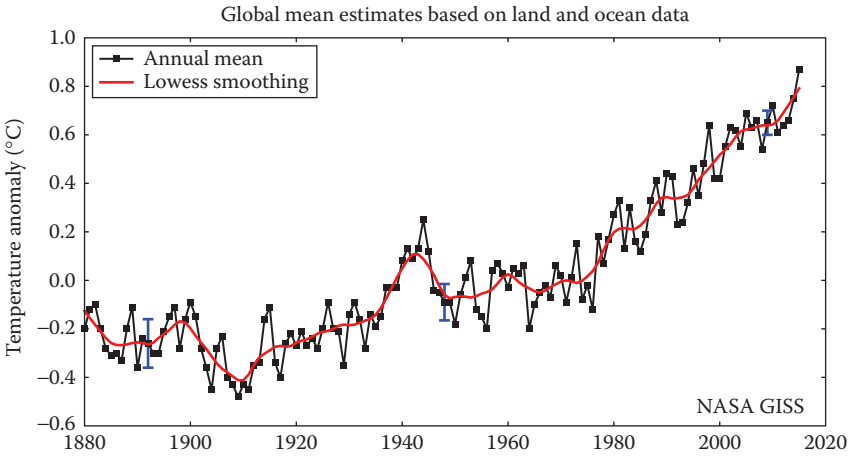


FIGURE 1.2 Hemispheric temperature change. (Courtesy of NASA Goddard Institute for Space Studies, New York.)

Except for a leveling off between the 1940s and the 1970s, the surface temperature of the Earth has steadily increased since 1880, and since the 1990s, it has increased at a faster rate in the northern hemisphere than in the southern hemisphere. The highest values ever recorded in both hemispheres have been reached in this decade (2000–2015). The current data from the National Aeronautics and Space Administration (NASA) Earth observatory (Figure 1.2) shows how the five-year running average continues to increase, especially after 1980. A warming of the climate system is unequivocal, and since the 1950s, many of the observed changes have been unprecedented over decades to millennia.

The IPCC's Fifth Assessment Report (2013) concluded that the scientific evidence for a warming climate is undeniable and that "human influence on the climate system is clear." Each of the last three decades has been successively warmer at the Earth's surface than any preceding decade since 1850 (see Figure 1.3), and the period 1983–2012 was *likely* the warmest 30-year period of the past 1400 years (*medium confidence*). The globally averaged combined land and ocean surface temperature data as calculated by a linear trend show a warming of 0.85°C (0.65°C–1.06°C), over the period 1880–2012, when multiple independently produced datasets exist.

The evidence for human influence has grown since 4th Assessment Report (AR4). The IPCC states (2013) that "it is *extremely likely* that human influence has been the dominant cause of the observed warming since the mid twentieth century." Figure 1.4 compares the observed and simulated climate changes based on three large-scale indicators in the atmosphere, the cryosphere, and the ocean: change in continental land surface air temperatures (yellow panels), Arctic and Antarctic September sea ice extent (white panels), and upper ocean heat content in the major ocean basins (blue panels). Global average changes are also given. Anomalies are given relative to 1880–1919 for surface temperatures, 1960–1980 for ocean heat content, and 1979–1999 for sea ice. All time series are decadal averages, plotted at the center of the decade. For temperature panels, observations are dashed lines if the spatial coverage of areas being examined is <50%. For ocean heat content and sea ice panels, the solid line is where the coverage of data is good and higher in quality, and the dashed line is where the data coverage is only adequate, and thus, uncertainty is larger (Figure 1.5).

The effects can be seen over ocean, land, and ice. Observations of climate changes from AR4 include warming throughout much of the world's oceans, increasing rates of global mean sea-level rise, changes in ocean salinity, acidification of the oceans, more frequent warm days and nights and fewer cold days and nights, reductions in the number of frost days, decreasing snow cover in most regions, degrading permafrost in extent and thickness, large-scale precipitation changes, increase in the number of heavy precipitation events, shrinking annual average Artic sea ice extent, widespread

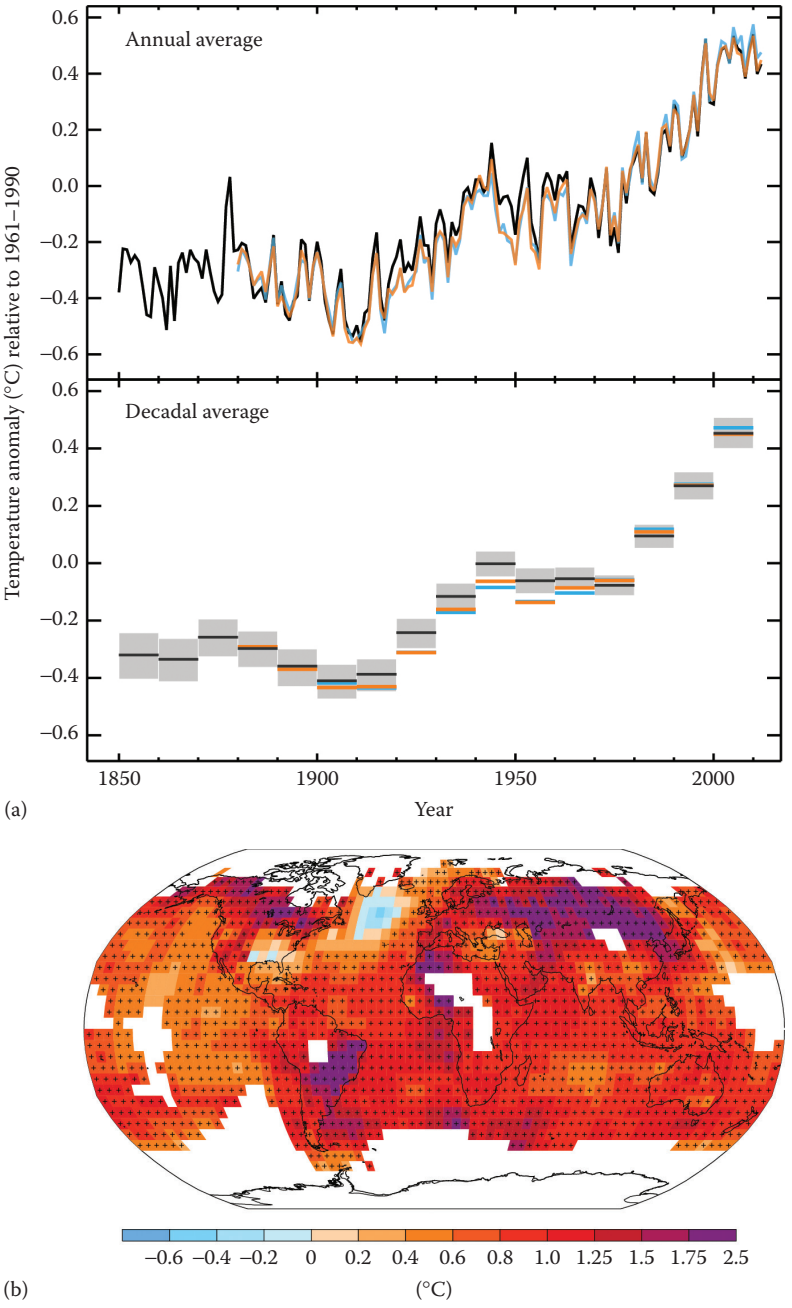


FIGURE 1.3 Observed changes in surface temperature: (a) observed globally averaged combined land and ocean surface temperature anomaly (1850–2012) and (b) observed change in surface temperature (1901–2012). (From IPCC, Climate change 2014: Impacts, adaptation, and vulnerability, In: *Working Group II Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Retrieved from http://www.ipcc.ch/pdf/assessment-report/ar5/wg2/ar5_wgII_spm_en.pdf, 2014.)

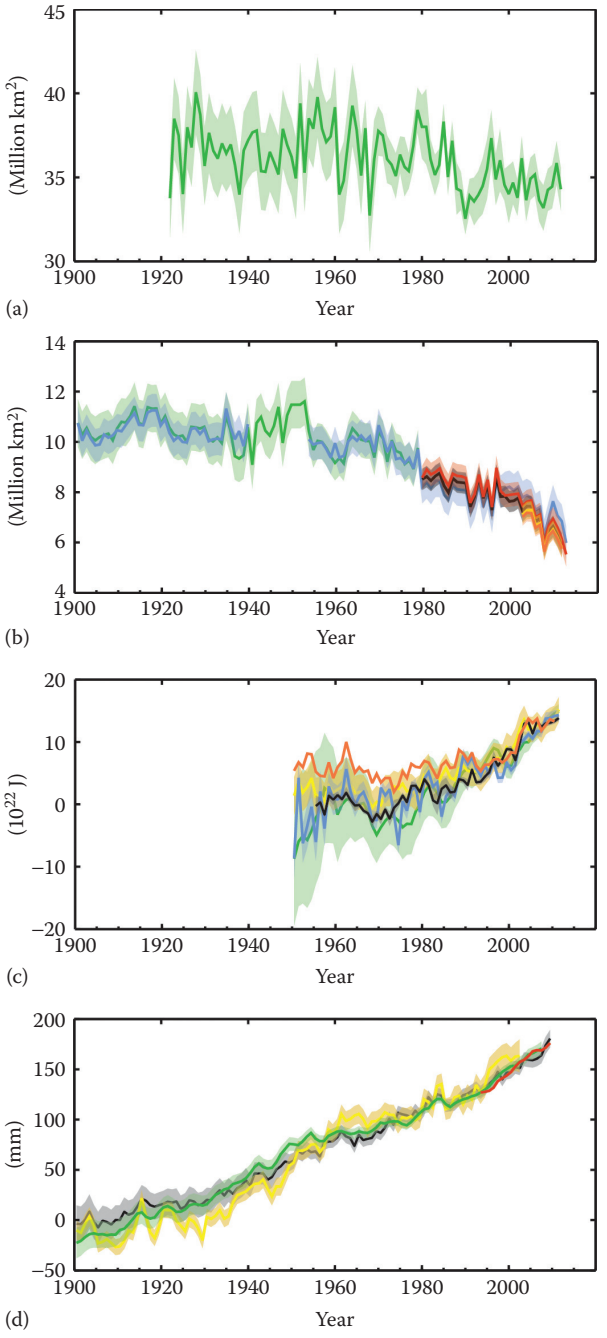


FIGURE 1.4 Climate change indicators: (a) northern hemisphere spring snow cover, (b) Arctic summer sea ice extend, (c) change in global average upper ocean heat content, and (d) global average sea-level change. (From IPCC, Summary for policymakers, In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, (eds.), Cambridge, Cambridge University Press, pp. 1–30. Retrieved February 10, 2016, from http://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_SPM_FINAL.pdf, 2013.)

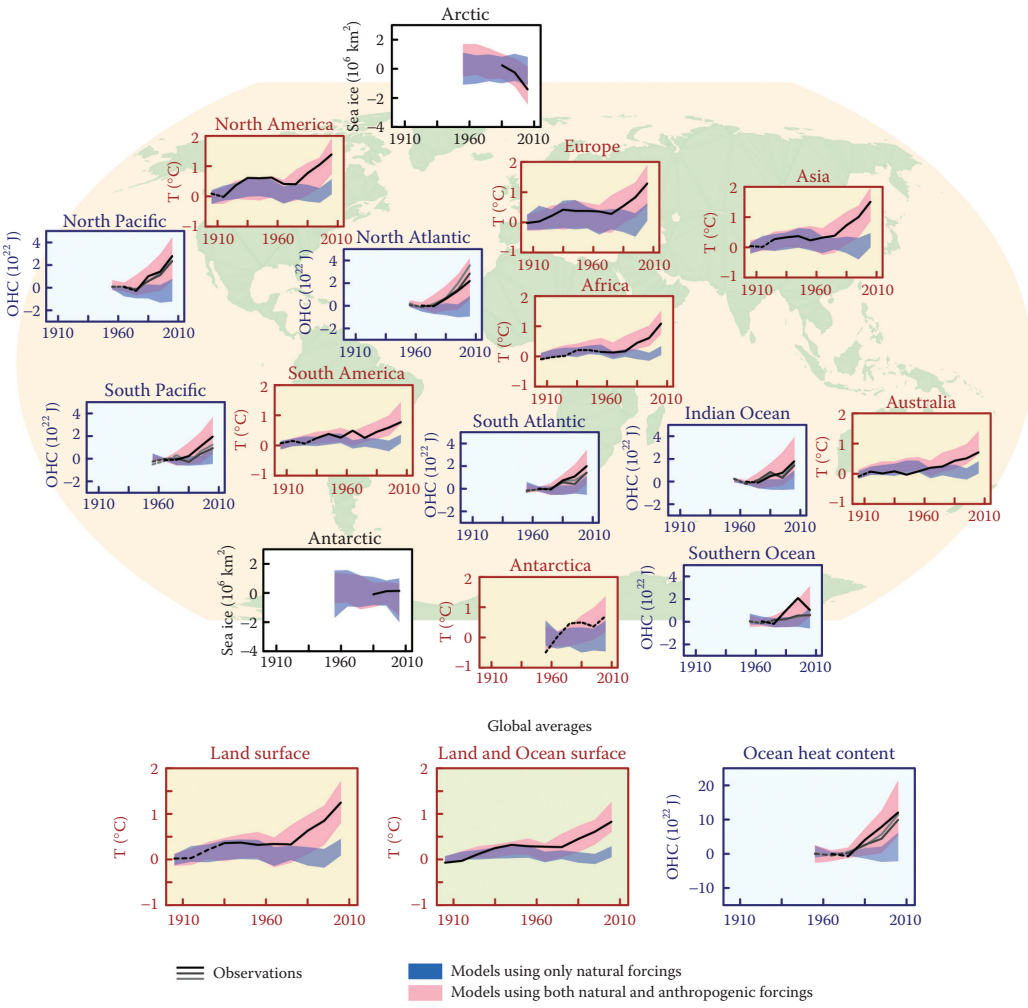


FIGURE 1.5 Hemispheric temperature change. (From IPCC, Summary for policymakers, In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, (eds.), Cambridge, Cambridge University Press, pp. 1–30. Retrieved February 10, 2016, from http://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_SPM_FINAL.pdf, 2013.)

glacier retreat, and changes in ice sheets in Greenland and Antarctica. These are all discussed in great detail in 5th Assessment Report (AR5) (IPCC, 2013).

The IPCC's Fifth Assessment Report concluded that the scientific evidence for a warming climate is undeniable and that "human influence on the climate system is clear" (IPCC, 2013), and also stated that "human influence has been detected in warming of the atmosphere and the ocean, in changes in the global water cycle, in reductions in snow and ice, in global mean sea level rise, and in changes in some climate extremes." Figure 1.4 shows several indicators of a changing global climate: (1) extent of Northern Hemisphere March–April (spring) average snow cover; (2) extent of Arctic July–August–September (summer) average sea ice; (3) change in global mean upper ocean (0–700 m) heat content aligned to 2006–2010, and relative to the mean of all datasets for 1970; and (4) global mean sea level relative to the 1900–1905 mean of the longest running dataset, and with all datasets aligned to have the same value in 1993, the first year of satellite altimetry data. All time

series (colored lines indicating different datasets) show annual values, and where assessed, uncertainties are indicated by colored shading. Trends for snow cover, sea ice extent, and upper ocean heat content and global average sea level are very clear.

A map produced by scientists at the Goddard Institute for Space Studies (Figure 1.6) shows the 10-year average (2000–2009) temperature change relative to the 1951–1980 mean. The most significant temperature increases are in the Arctic and the Antarctic Peninsula, and the near-record temperatures of 2009 occurred despite an unseasonably cool December in much of North America. The warming trend is clear and warming continues. According to the NASA's Goddard Institute for Space Studies, the warmest year since modern record-keeping began in 1880, was 2015 (Figure 1.7). The record-breaking

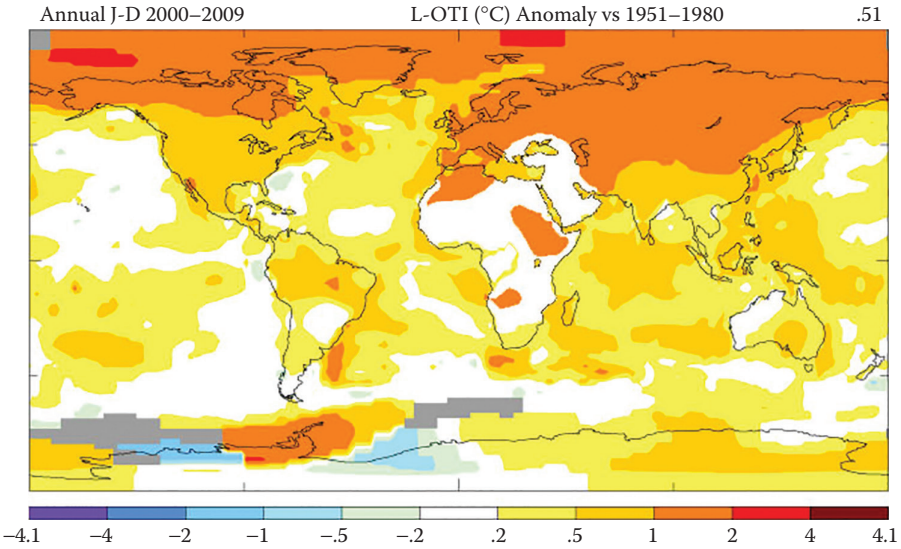


FIGURE 1.6 Ten-year average (2000–2009) temperature change relative to the 1951–1980 mean. (Courtesy of NASA Goddard Institute for Space Studies, New York.)

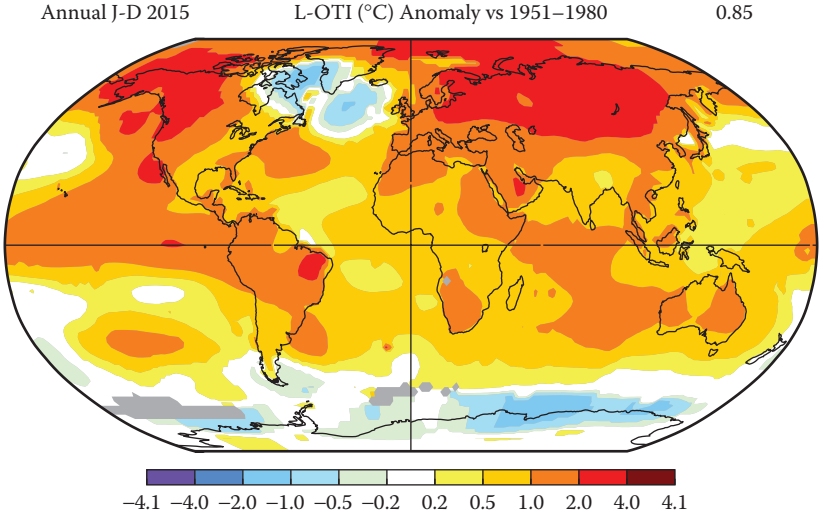


FIGURE 1.7 Annual anomaly (2015) relative to the 1951–1980 mean. (Courtesy of NASA Goddard Institute for Space Studies, New York; NSA/GSFC/Scientific Visualization Studio.)

year continues a long-term warming trend in which 15 of the 16 warmest years on record have occurred between 2001 and 2015, the latest year for which data was available for this edition.

In fact, globally averaged temperatures in 2015 were higher than the previous mark set in 2014 by 0.13°C, and 2015 was the first time the global average temperatures were 1°C or more above the 1880–1899 average. Only once before, in 1998, has the new record been greater than the old record by this much. NOAA scientists agreed with the finding that 2015 was the warmest year on record based on separate, independent analyses of the data. Because weather station locations and measurements change over time, there is some uncertainty in the individual values in the GISS Surface Temperature Analysis (GISTEMP) index. Taking this into account, NASA analysis estimates that 2015 was the warmest year with 94% certainty. Much more information is available at the NASA global climate change site: http://climate.nasa.gov/vital-signs/global-temperature/.

1.3 EFFECTS OF CLIMATE CHANGE

There are many comprehensive reports discussing the origins and effects of climate change; probably, the most detailed are published by the IPCC and available from its website (http://www.ipcc.ch). The most recent one from 2014 on impacts, adaption, and vulnerability clearly states that "In recent decades, changes in climate have caused impacts on natural and human systems on all continents and across the oceans. Evidence of climate-change impacts is strongest and most comprehensive for natural systems." It also states that "Impacts from recent climate-related extremes, such as heat waves, droughts, floods, cyclones, and wildfires, reveal significant vulnerability and exposure of some ecosystems and many human systems to current climate variability (very high confidence)."

In the IPCC report by Yohe et al. (2007), the authors describe the impacts of several climate scenarios on human welfare as expressed by different global average temperatures. In the report, they outline the effects on water, ecosystems, food, coastline, and health as well as the time dimension. It is clear that even with the scenario with the smallest increase in temperature, impacts should be expected. Therefore, even if effective policies are implemented and anthropogenic emissions are quickly reduced to preindustrial levels, our planet will still experience a significant degree of climate change with important worldwide effects on the world's environment, economy, and society. This work was updated in the IPCC's report "Climate Change 2014 Impacts Adaptation, and Vulnerability," which shows multiple impacts all over the world. Figure 1.8 shows some recent impacts attributed to climate change, based on studies since the AR4, which is divided in three parts: (a) It includes the global patterns of impacts in recent decades attributed to climate change, based on studies since the AR4. Impacts are shown at a range of geographic scales. Symbols indicate the categories of attributed impacts, the relative contribution of climate change (major or minor) to the observed impact, and confidence in attribution. Additional tables in the report describe the impacts, and in most of them, there is a medium or high confidence that most of the impacts are due to climate change. (b) It describes the average rates of change in distribution (kilometers per decade) for marine taxonomic groups based on observations over 1900–2010. Positive distribution changes are consistent with warming (moving into previously cooler waters, generally poleward). The number of responses analyzed is given within parentheses for each category. (c) This is a summary of estimated impacts of observed climate changes on yields over 1960–2013 for four major crops in temperate and tropical regions, with the number of data points analyzed given within parentheses for each category. Yields are reduced in all crops.

The physical, ecological, social, and economic effects of climate change are numerous and the subject of many specialized publications, and out of the scope of this book. According to the IPCC, the extent of climate change effects on individual regions will vary over time and with the ability of different societal and environmental systems to mitigate or adapt to change. Climate change will positively impact some regions and negatively other regions. However, "Taken as a whole, the range of published evidence indicates that the net damage costs of

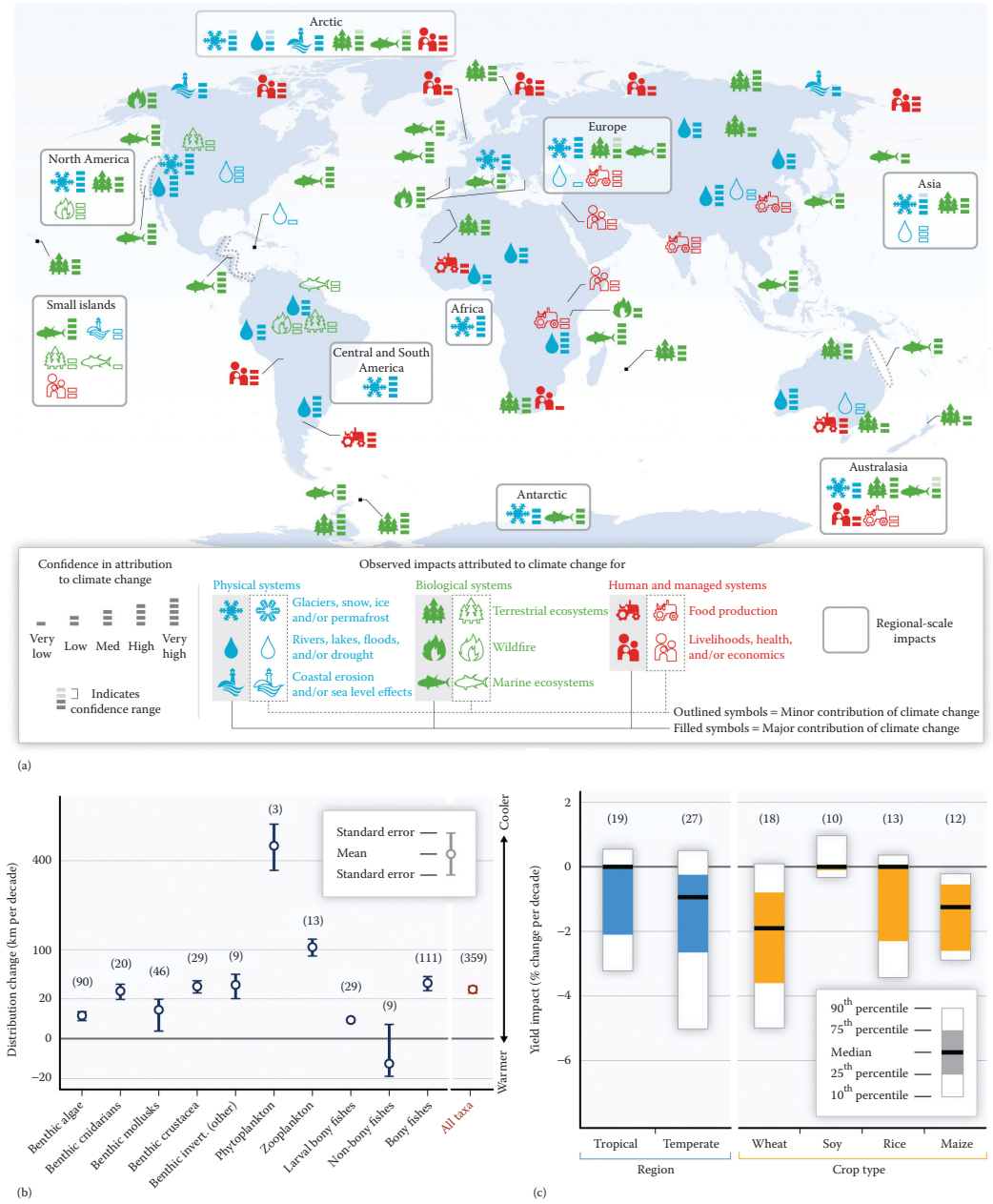


FIGURE 1.8 Climate change impacts. (From IPCC, Climate change 2014: Impacts, adaptation, and vulnerability, In: *Working Group II Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Retrieved from http://www.ipcc.ch/pdf/assessment-report/ar5/wg2/ar5_wgII_spm_en.pdf, 2014.)

climate change are likely to be significant and to increase over time" (IPCC, 2007), this has been confirmed by multiple independent reports.

Climate models have improved since the AR4. Models reproduce observed continental-scale surface temperature patterns and trends over many decades, including the more rapid warming since the mid twentieth century and the cooling immediately following large volcanic eruptions (*very high confidence*) (IPCC, 2014).

Many of the impacts of climate change will affect the built environment. It is virtually certain that over most land areas, warmer and fewer cold days and nights, and warmer and more frequent hot days and nights will produce reduced energy demand for heating and increased demand for cooling. Air quality will decline in cities, and there will be reduced disruptions to transportation due to snow and ice, but there will be effects on winter tourism. It is very likely that warm spells/heat waves will increase in frequency over most land areas and produce a reduction in quality of life for people in warm regions without appropriate housing, negatively impacting the elderly, very young, and the poor. It is very likely that heavy precipitation events will increase in frequency over most areas and produce disruption of settlements, commerce, transport, and societies due to flooding. There will be pressures on urban and rural infrastructures and loss of property. It is likely that the areas affected by droughts will increase, producing water shortages for settlements, industry, and societies, and reduce hydropower generation potentials and the potential for population migration. It is likely that intense tropical cyclone activity will increase producing disruption by flood and high winds, withdrawal of risk coverage in vulnerable areas by private insurers, the potential for population migrations, and loss of property. It is likely that there will be increased incidence of extreme high sea level (excludes tsunamis) that will increase the costs of coastal protection versus the costs of land-use relocation and also increase the potential for movement of populations and infrastructure (IPCC, 2014).

In general, heat-related mortality in many urban centers will increase not only in warm climates but also in more temperate climates such as London. Coasts will be exposed to increasing risks, including coastal erosion; millions of people will be flooded every year due to sea-level rise by the 2080s, especially in densely populated, low-lying areas, such as the mega-deltas of Asia and Africa and small islands. The most vulnerable industries, settlements, and societies are usually those in coastal and river flood plains, those whose economies are closely linked with climate-sensitive resources, and those in areas prone to extreme weather events, especially where rapid urbanization is occurring. Poor communities can be especially vulnerable, in particular those concentrated in high-risk areas. They tend to have more limited adaptive capacities and are more dependent on climate-sensitive resources such as local water and food supplies. We must be ready for these changes, and architecture will have to adapt to climate change. For example, in many coastal communities or flood prone areas, homes should be designed with an expendable part of it that will disappear in a flood.

1.4 GREENHOUSE GAS EMISSIONS FROM BUILDINGS

Total radiative forcing is positive and has led to an uptake of energy by the climate system. The largest contribution to total radiative forcing has been caused by the increase in the atmospheric concentration of CO_2 since 1750 (IPCC, 2014). It is also clear that temperatures are affected by GHG levels and that global mean surface temperatures will rise as a function of cumulative total global CO_2 emissions (Figure 1.9) (IPCC, 2014). Multimodel results from a hierarchy of climate carbon cycle models for each Representive Concentration on Pathways (RCP) until 2100 are shown with colored lines and decadal means (dots). Some decadal means are labeled for clarity (e.g., 2050 indicating the decade 2040–2049). Model results over the historical period (1860–2010) are indicated in black. The colored plume illustrates the multimodel spread over the four RCP scenarios and fades with the decreasing number of available models in RCP8.5. The multimodel mean and range simulated by Coupled Model Intercomparison Project 5 (CMIP5) models, forced by a CO_2 increase of 1% per year (1% per year CO_2 simulations), are given by the thin black line and gray area. For a specific amount of cumulative CO_2 emissions, the 1% per year CO_2 simulations exhibit lower warming than those driven by RCPs, which include additional non-CO_2 forcing. Temperature values are given relative to the 1861–1880 base period and emissions relative to 1870. Decadal averages are connected by straight lines (IPCC, 2014).

It is difficult to determine the exact amount of energy used by the building sector because it is generally not considered an independent sector with its own data. Furthermore, there is a lack of

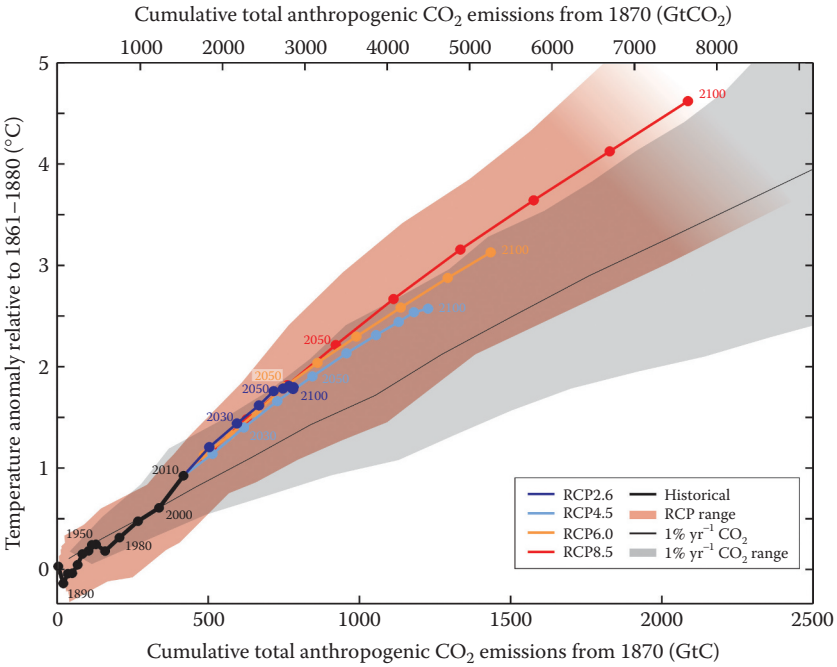


FIGURE 1.9 Global mean surface temperature increases as a function of cumulative total global CO_2 emissions.

consistent data from the different entities that collect this information. Different sources estimate GHG emissions from the building sector to represent ~33% of emissions worldwide, according to the UNEP Sustainable Buildings and Climate Initiative (SBCI) (UNEP SBCI, 2010). The International Energy Agency (IEA) also estimates that the building sector contributes to approximately one-third of global final fuel and power consumption (IEA, 2010) while emitting 8.1 Gt of CO_2 per year (IEA, 2011). In many industrialized more developed nations, this number is higher, and in the United States, estimates range from 43% (Brown et al. 2007) to 49% (Mazria and Kershner, 2008) of total emissions. What is evident is that all of these numbers are significant, and building emissions are always the single largest source, higher than emissions from industry and transportation. Furthermore, these only include emissions from energy use in the building, and if other building-related emissions such as embodied carbon were considered, the number would be significantly higher. The IPCC's Fourth Assessment Report (IPCC AR4) estimated that building-related GHG emissions reached 8.6 billion metric tons (t) CO_2e in 2004 and could nearly double by 2030, reaching 15.6 billion tCO_2e under its high-growth scenario. This means that just from the sheer quantity of these emissions, to have any real impact on climate change, it is crucial that emissions from the building sector be addressed and reduced. Furthermore, according to this same report, buildings provide the most economic mitigation potential for reduction of GHG emissions and the largest potential for reducing GHG emissions and are relatively independent of the price of carbon reduction (cost per tCO_2e) applied (Figure 1.10). With proven and commercially available technologies, the energy consumption in both new and existing buildings can be cut by an estimated 30%–50% without significantly increasing investment costs. According to the IEA's Energy Technology Perspectives 2010 (IEA, 2010), to be on track to limit global warming to 2°C–3°C, global averaged GHG emissions in the buildings sector should be reduced by 12.6 Gt of CO_2 per year by 2050 against the baseline scenario.

The IPCC states that measures to reduce GHG emissions from buildings fall into one of the three categories: (1) reducing energy consumption and embodied energy in buildings; (2) switching to

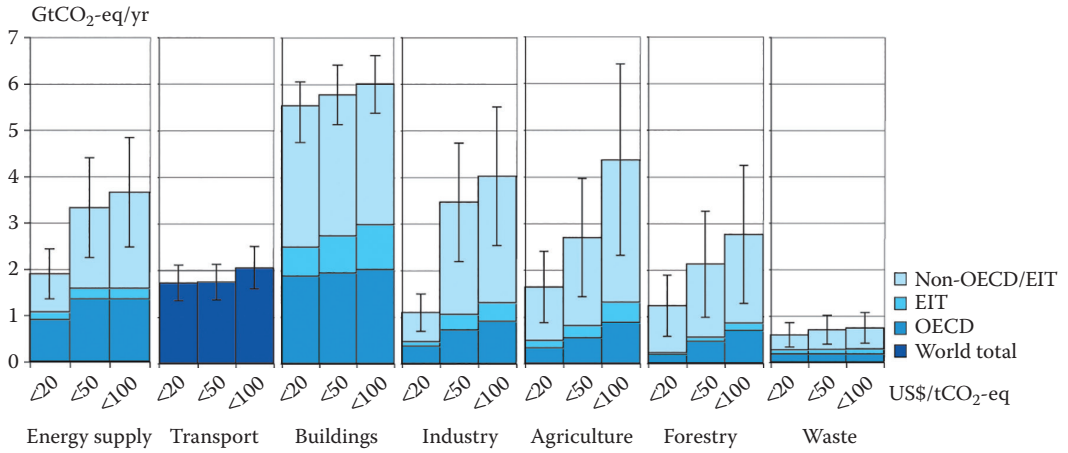


FIGURE 1.10 Estimated economic mitigation potential by sector and region using technologies and practices expected to be available in 2030. The potentials do not include nontechnical options such as lifestyle changes. OECD, Organization for Economic Cooperation and Development; EIT, Economies in Transition. (From Parry, M.L. et al. eds., *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge, Cambridge University Press, 2007, Figure SPM.6. With permission.)

low-carbon fuels, including a higher share of renewable energy; or (3) controlling the emissions of non-CO_2 GHG. A very large number of technologies that are commercially available and tested in practice can substantially reduce energy use while providing the same services and often substantial co-benefits.

In another very comprehensive report published by the American Solar Energy Society to investigate different climate change mitigation strategies (Brown et al. 2007), scientists estimated that 43% of U.S. carbon dioxide emissions result from the energy services required by residential, commercial, gas, and industrial buildings, and that there was a huge potential for reduction in emissions by increasing the efficiency of buildings: 688 Mt of CO_2 per year in 2030 compared with 63 for concentrating solar, 63 for photovoltaics, 181 for wind, 53 for biofuels, 75 for biomass, and 83 for geothermal. This has been reinforced by multiple reports that always state that efficiency is the most cost-effective way to reduce energy consumption and carbon emissions in buildings (Jennings et al. 2011). Implementing energy efficiency standards in appliances has been among the most effective policies to reduce overall energy consumption (Jennings et al., 2011). The IEA recommends that buildings should include energy performance labels or certificates that provide information to owners, buyers, and renters (IEA, 2011a). Even in countries where buildings are not designed to last long, they last longer than appliances, which usually last less than 20 years. This means that any improvement in building performance will probably have a larger impact than an improvement in appliance efficiency (Figure 1.11).

It is clear that significant reductions in emissions will be possible only if reductions in emissions due to energy consumption in buildings are implemented. However, in addition to energy, buildings also emit GHGs during their construction, by the water that they use, and through the waste that they produce (Malin, 2008).

Emissions are produced by the building, its interactions with the environment around it, which can be affected by the building fabric and materials (Figure 1.12) or the building's inputs and outputs (operation, construction, water, waste, and even the site work around the building).

These factors can be described by the following equation:

$$T_{be} = O_e + C_e + W_e + W_a \tag{1.1}$$

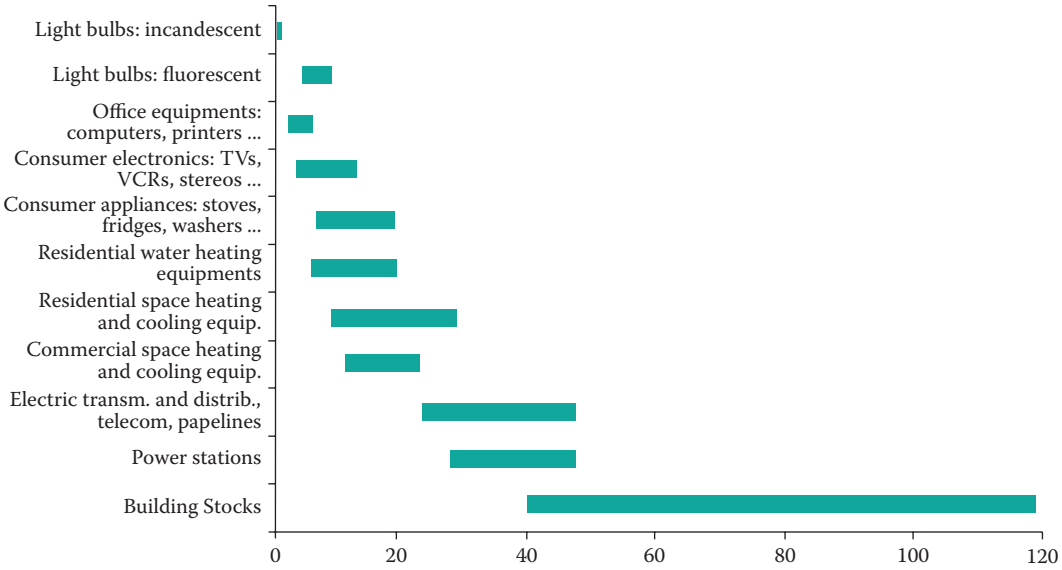


FIGURE 1.11 Typical lifespan of building appliances, services, and stock. (From Grantham Institute/International Energy Agency Workshop, London.)

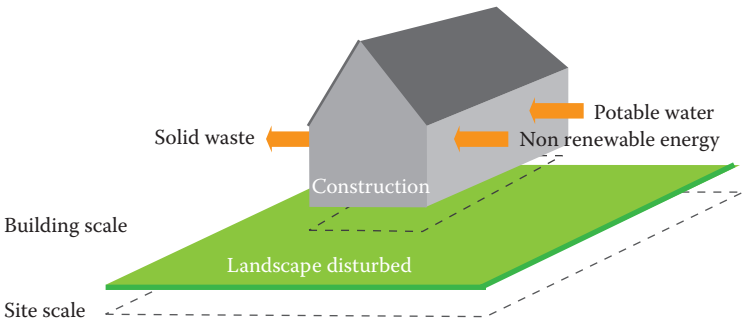


FIGURE 1.12 Building emissions and environmental interactions.

where:

T_{be} is the total building emissions
O_e is the operation emissions (energy)
C_e is the construction emissions
W_e is the water emissions
W_a is the waste emissions

Site work in the landscape can also release carbon sequestered in the ground or plants. Emissions from transportation are also very important and are affected by building location but are not produced by the building itself or its inputs and outputs, and are thus not considered part of a building's emission in this book.

1.4.1 Operation Emissions (O_e)

Operation emissions are produced from energy used to operate the buildings, and it is probably the single largest source of building-related GHG emissions (80%), according to UNEP SBCI (2010).

This percentage can vary significantly depending on the embodied energy of the building materials, the type of building, and the climate. To reduce emissions from building operation, energy consumption must be significantly reduced so that buildings have the lowest energy consumption possible.

1.4.1.1 Net Zero Energy Buildings

A net zero energy building (NZEB), also known as a zero energy building (ZEB), zero net energy (ZNE) building, or net zero building has greatly reduced energy needs through efficiency gains such that the balance of the energy needs can be supplied by renewable technologies (Torcellini et al. 2006). A NZEB produces enough renewable energy to meet its own annual energy consumption requirements, reducing the use of nonrenewable energy in the building sector. The U.S. Department of Energy (2015) states that a zero energy building is an energy-efficient building, where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy. Typically, a NZEB must demonstrate this with actual annual measurements.

A NZEB is usually connected to the electrical grid. The building uses energy from the grid when renewable energy produced on-site is not enough to meet its needs and then sends surplus energy to the grid when it generates more energy than it uses. In a NZEB, the grid acts as the battery for storage. Batteries are seldom used unless there is no access to the grid. However, as battery technology improves, they are beginning to be implemented in different ways. For example, they have been installed in some buildings in Irvine, California, with software that switches the buildings to battery power when electricity demand on the power grid is high, relieving some stress on the power grid during peak times. Also if NZEBs become more common, there will be a need for storage during times of maximum production.

All NZEBs must have a boundary that defines the area within which the renewable systems are located and where delivered and exported energy is measured. This boundary can be around the building footprint if the on-site renewable energy is located within the building footprint, or around the building site if some of the on-site renewable energy is on-site but not within the building footprint. Delivered energy and exported energy are measured at the site boundary (Figure 1.13) (DOE, 2015).

Depending on where the energy is measured, there are two common definitions of net zero energy: net zero site energy and net zero source energy.

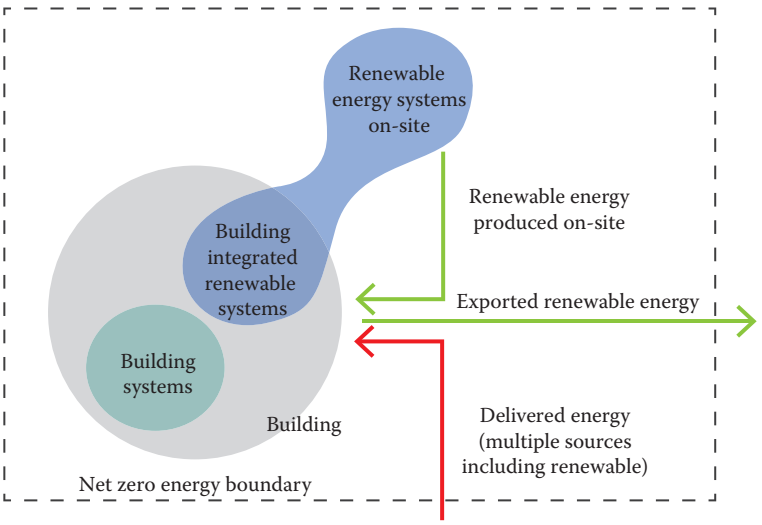


FIGURE 1.13 NZEBs and boundary.

1.4.1.1.1 Net Zero Site Energy Building

A net zero site energy building produces as much energy as it uses, when accounted for at the site. Renewable energy can be produced at the site and is accounted in the same units as nonrenewable energy that comes into the site (Torcelini, 2006). The main advantage of a net zero site definition is that it is easy to understand and measure, typically using meters (electric and gas). The amount of energy entering the site and measured at the boundary must be equal to or lower than the amount of energy coming out. Another advantage of this definition is that it has the fewest fluctuations because it is based on constant values; variations in the power source mix or energy costs do not affect the balance. The accounting is simply based on the comparison between the incoming energy and the outgoing energy. This definition does have some limitations, for example, it does not consider the site to source conversion factors, differing costs of energy sources, or even of the same source of energy at the same time. To measure GHG emissions and carbon neutrality, the fact that it does not properly account for the power source mix is also a limitation when counting emissions. The net zero site energy only measures the amount of energy used in the site without considering where this energy came from and that dirtier sources of energy would require more renewable energy to offset it. Also, a building could be net zero site energy but still has an energy cost because the energy used at peak hours has a different cost than the energy returned to the grid.

Site energy can be useful to understand the performance of the building and its building systems, encouraging the implementation of passive strategies and efficient systems, but it provides an incomplete picture of the impacts from resource consumption and emissions associated with the energy use.

1.4.1.1.2 Net Zero Source Energy Building

A net zero source energy building produces as much energy as it uses as measured at the source, where this energy is produced. This definition accounts for conversion factors: to calculate a building's total source energy, both imported and exported energies are multiplied by the appropriate site-to-source energy factors (Torcellini et al., 2006). To perform this calculation, power generation and transmission factors are needed. Source energy is calculated from delivered energy and exported energy for each energy type using source energy conversion factors that account for electricity losses from generation to arrival on-site. These source energy conversion factors are applied to convert energy delivered and exported on-site into the total equivalent source energy. Because losses are accounted for by multiplying the site energy by the conversion factors, the *real* amount of energy used by the building can be calculated. Source energy tells us how much energy was actually produced to deliver a certain amount of energy used on site. Table 1.2 summarizes the national average source energy conversion factors for various energy types (DOE, 2015). One important observation is that even though exported electricity is clean renewable energy generated on-site with a smaller conversion factor, it has the same conversion factor than energy generated off-site, so as to be able to correctly account for the same amount of electricity that is being displaced from the grid. A net zero source energy building gives a closer representation of the actual consumption of resources, measured in units of energy, than an NZE site building, though it is also a bit more difficult to understand and calculate.

Two other less common definitions for net zero buildings are NZE cost and NZE emissions building. A NZE cost receives as much financial credit for exported energy as it is charged on the utility bills. The credit received for exported electricity (often referred to net energy generation) will have to offset energy, distribution, peak demand, taxes, and metering charges for electricity and gas use (Torcellini et al. 2006). An emission-based ZEB produces at least as much emission-free renewable energy as it uses from emission-producing energy sources. In this case, changes in the power source mix are accounted for.

The International Energy Conservation Code (IECC) includes a Zero Energy Performance Index (zEPI) that also helps to understand NZE buildings and their position in relation to energy use in existing buildings. The zEPI is a value that represents the ratio of the energy performance of a proposed building design to the average energy performance of buildings with similar occupancy and climate types, benchmarked to the year 2000. It is a ratio of a proposed building's predicted Energy Use Intensity

TABLE 1.2
National Average Source Energy Conversion Factors

Energy form	Source energy conversion factor (r)
Imported electricity	3.15
Exported renewable electricity	3.15
Natural gas	1.09
Fuel oil (1, 2, 4, 5, 6, Diesel, Kerosene)	1.19
Propane and liquid propane	1.15
Steam	1.45
Hot water	1.35
Chilled water	1.04
Coal or other	1.05

Source: DOE (2015).

(pEUI) to the Energy Use Intensity (EUI) of a baseline or reference building model, multiplied by 100 to give a scalar value, which can range from 0 (for a ZEB) to 100 (for a building that uses the same amount of energy as the baseline model). The number compares a building's performance with the reference building. The lower the value, the better the energy performance (uses that percentage of energy compared to the reference), and a value of 0 represents a NZE building. The 2012 IECC requires a zEPI of 57; the 2012 International Green Construction Code requires a zEPI of 51, which represents a 10% increase in efficiency over the 2012 IECC (AIA, 2008). The IECC index is based on the source energy. A building that is NZE source would be zero, and a building that is generating more energy than it is using would have a negative value.

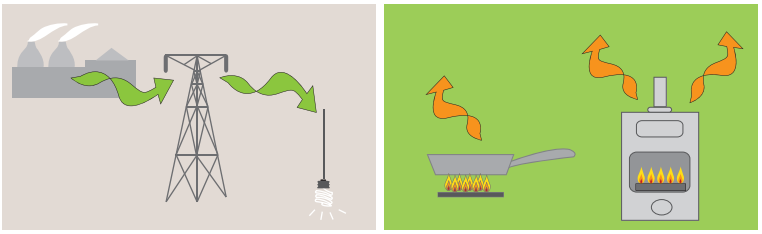
1.4.1.2 Classification of Greenhouse Gases in Terms of Scopes

The UNEP proposes, and most GHG protocols have adopted, a classification of GHG in terms of scopes that measure emissions only during the use phase (e.g., operation, maintenance, and retrofits) of the building. It proposes three scopes that are commonly used in most GHG protocols.

Scope 1: Direct on-building-site or on-building-stocks GHG emissions: Direct on-building-site GHG emissions result from sources within the boundaries of the building or building stocks under study that can be quantified by the reporting entity, including stationary combustion emissions from fuels and combustion from boilers, furnaces or turbines, and fugitive emissions from intentional or unintentional releases.

Scope 2: Indirect on-building-site GHG emissions: Indirect on-building-site GHG emissions are sometimes called indirect energy emissions. They are a consequence of the activities that occur outside the building site, for example, activities at a community power plant in the process of providing the energy consumed on-building site. Scope 2 emissions include those produced from the generation of energy that is used in the building. These include all GHG emissions associated with the overall generation of purchased energy such as electricity or steam for cooling, ventilation, or heating.

Scope 3: Other indirect GHG emissions: Scope 3 addresses indirect emissions not covered in scope 2 activities that are relevant to building performance and not included in the common carbon metric. Examples of these include upstream and downstream emissions



Sources of indirect emissions Sources of direct emissions

FIGURE 1.14 Indirect and direct building emissions.

related to the before-use phase of the buildings (e.g., raw material extraction for construction materials), transportation-related activities during all stages of the building life cycle, and after-use activities such as reuse and recycling of building components. Some protocols such as the protocol developed by DEFRA divide transportation into two groups and include owned transportation in scope 1 and other transport-related activities such as commuting in scope 3 (Figure 1.14).

1.4.2 Construction Emissions (C_e)

Embodied carbon measures the carbon emitted into the atmosphere during the construction of the buildings. It is difficult to estimate the amount of carbon embodied in the building construction materials, because it is affected by the amount of energy needed to extract the raw materials to fabricate the material, the transportation of the material to the site, the life of the building, the construction process, including the disturbance of the site, the maintenance of the building materials, and the end of use management of the building materials after they are no longer needed.

1.4.3 Emissions from Water (W_e)

Water consumption in the building also generates GHG emissions when it is pumped from the source and treated for consumption. As the wastewater from the building is treated to remove physical, chemical, and biological contaminants, energy is generated in this process. These emissions are different from domestic water heating emissions, which are included in the energy and operation of the building. In California, research performed by the California Energy Commission has found that water and energy resources are strongly connected, establishing a water–energy nexus. Transportation and treatment of water, treatment and disposal of wastewater, and the energy used to heat and consume water account for nearly 20% of the total electricity (48 terawatt-hours [TWh] per year) and 30% of nonpower plant-related natural gas consumed in California (California Energy Commission, 2016).

1.4.4 Emissions from Waste (W_a)

Solid waste (not transported in water) coming from the building must be taken from the building and treated, which generates emissions. In addition, the waste that arrives at the landfill usually produces methane while it is decomposing. Materials and land management-related activities such as recycling of municipal solid waste, waste-to-energy recovery systems, and source reduction and recycling result in the avoidance of GHG emissions from waste.

1.5 CARBON-NEUTRAL ARCHITECTURAL DESIGN

Kilroy et al. (2006) define carbon-neutral design as a movement focusing on creating buildings that reduce or eliminate carbon dioxide emissions throughout a building's life cycle. A typical building

generates carbon emissions throughout its life span. Before construction, carbon is emitted when raw materials are processed into building materials and products. During construction, this occurs when building materials are transported to the construction site, when the site is excavated for construction, and when equipment and tools are operated. Once construction is complete, carbon emissions are generated from the building's operation, including mechanical systems, lighting, and appliances. Still more carbon is emitted at the end of the building's life, as the building materials are reused, recycled, or sent to a landfill. The protocol developed for the carbon neutral design project (http://www.tboake.com/carbon-aia/) includes scope 1 as well as scope 2 emissions and estimates that energy used in building operation accounts for ~70% of the carbon emissions associated with a building.

Some definitions of carbon neutral architecture only consider emissions from energy. Architecture 2030 defines a carbon-neutral building as one in which no fossil fuel GHGs are emitted to operate the building, which includes emissions from heating, cooling, and lighting. Carbon neutrality may be accomplished by implementing innovative sustainable design strategies, generating on-site renewable power and/or purchasing (20% maximum) renewable energy and/or certified renewable energy credits. If only energy is considered to calculate emissions, then the process to count them would be as follows:

1. As in an NZEB, the first step is to define the boundaries of the site. Typically, this is where energy is counted and the meters are located.
2. The next step is to measure the energy flows across the defined boundary. Typical flows are from electricity and gas.
3. The energy flows must be multiplied by carbon dioxide factors (use tables such as Table 1.3).
4. Finally, the values obtained from the calculation of the different sources in step 3 are added to determine total annual CO_2 emissions.

TABLE 1.3
Conversion Factors for Electricity and Natural Gas from the United Kingdom's Department of Energy and Climate Change

		Fuel type		Measurement unit	Emissions factor $kgCO_2$/per measurement unit
Phase I	2010/2011–2013/2014	Electricity		kWh	0.5410
		Natural gas*		kWh	0.1836
Phase II	2014–2015	Electricity	On-site generate and self-supplied	kWh	0.490230
			Grid	kWh	0.533100
		Natural gas*		kWh	0.184557
	2015–2016	Electricity	On-site generate and self-supplied	kWh	0.458500
			Grid	kWh	0.496360
		Natural gas*		kWh	0.184070

* This conversion factor should be used for any gas supplied through the national grid network.

The United Kingdom's Department of Energy and Climate Change (DECC) has developed a series of guidelines surrounding the use of the term carbon neutrality, to discourage "greenwashing" and provide greater clarity around the concept. According to their definition, "Carbon neutral means that – through a transparent process of calculating emissions, reducing those emissions and offsetting residual emissions – net carbon emissions equal zero." (UK Department of Energy and Climate Change, 2015).

To achieve carbon neutrality, energy consumption must first be reduced as much as possible. The first step is to improve efficiency by implementing energy conservation measures, the next step is the implementation of passive heating and cooling strategies, then high-performance Heating, Ventilation and Air Conditioning (HVAC) systems, and finally installing on-site renewable energy systems. If there are still emissions remaining, they can be offset. Because renewables are more expensive than energy conservation measures and require additional space that might not be available on-site, some designers use a rule of thumb of an 80% reduction from a reference building, meeting the remaining 20% with renewable energy and/or carbon offsets. If emissions from other sources such as water and waste are to be offset, then the building should become a plus energy building to compensate for the additional emissions. A truly carbon-neutral building has to be energy positive.

A carbon-neutral building is one in which total emissions are equal to zero. Carbon neutrality is accomplished by reducing the emissions in the different categories as much as possible and then offsetting the emissions. There are differences based on the emissions that are considered, but the definition is the same; emissions produced must be offset by renewable sources. If only emissions from energy are considered, then Equation 1.2 is used. In this case, the emissions from nonrenewable energy are offset by the generation of renewable energy (or partially by carbon offsets).

$$0 \geq T_{be} = O_e - R_s \tag{1.2}$$

where:

T_{be} is the total building emissions
O_e is the operation emissions (energy)
R_s is the renewable strategies

If, in addition to energy, water, waste, and construction are also considered, then the emissions from these must be added to the emissions from energy and Equation 1.3 is used. In this case, the emissions offset from the production of renewable energy have to offset all the other emissions, and the building is net positive for energy though still net zero for carbon.

$$0 \geq T_{be} = O_e + C_e + W_e + W_a - R_s \tag{1.3}$$

where:

T_{be} is the total building emissions
O_e is the operation emissions (energy)
C_e is the construction emissions
W_e is the water emissions
W_a is the waste emissions
R_s is the renewable strategies

If transportation is also considered, then it should also be included and Equation 1.4 is used. The building has to produce even more renewable energy to offset emissions from transportation.

$$0 \geq T_{be} = O_e + C_e + W_e + W_a + T_e - R_s \tag{1.4}$$

where:

T_{be} is the total building emissions
O_e is the operation emissions (energy)
C_e is the construction emissions
W_e is the water emissions
W_a is the waste emissions
T_e is the transportation emissions
R_s is the renewable strategies

Renewable strategies (R_s) offset the emissions generated by the building. If total building emissions, including renewables, are lower than or equal to zero ($0 \geq T_{be}$), then the building is carbon neutral. Any strategy that reduces emissions is a carbon-neutral design strategy, and if it offsets emissions, such as renewable energy, it acts as a sink.

1.6 COMMITMENTS TO REDUCE CARBON EMISSIONS

International efforts have been ongoing for many years to reduce anthropogenic impacts on climate change, and probably, the most important are the climate conferences. At the Paris Climate Conference (COP21) in December 2015, 195 countries adopted a legally binding global climate deal. The agreement sets out a global action plan to put the world on track to avoid climate change by limiting global warming to values between 1.5°C and 2°C. The agreement is due to enter into force in 2020 after 55 countries that account for at least 55% of global emissions have deposited their instruments of ratification.

In addition to this international treaty, several countries are developing regulations to reduce GHG emissions. The European Union has a target to reduce emissions by at least 40% by 2030 and in the United Kingdom, the Climate Change Act of 2008 legally commits the UK government to reducing CO_2 emissions by 80% by 2050 (DECC, 2009c, DECC, 2009b). The government is also committed to meeting its share of the European renewable energy target (20% of Europe's energy from renewables by 2020) by providing 15% of the UK's energy by renewable sources by 2020 (DECC, 2009c). The National Energy Efficiency Action Plan sets a target to reduce emissions from the UK's residential housing stock to 107.43 $MtCO_2$ (a 31% reduction) by 2020. The government is clearly stating goals that go beyond energy and that are based on carbon emissions.

An important policy affecting energy and CO_2 performance of nondomestic buildings in the European Union is the Energy Performance of Buildings Directive (EPBD), part of European legislation that all member states must adopt. The EPBD requires that all new buildings must be nearly zero energy by 2020. A nearly zero building is defined as one that "… has a very high energy performance … [the] very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site." The quantitative value of "nearly zero" is left to each member state to define but is to be tied to primary energy demand. The directive includes the following measures that address energy performance to reduce emissions (CLG, 2008c):

- Introduction of energy performance certificates
- Requirement of public buildings to display energy certificates (DECs)
- Requirement of inspections for air-conditioning systems

A DEC (Figure 1.15) shows the energy performance of a building based on actual energy consumption as recorded over the last 12 months within the validity period of the DEC (the operational rating). The operational rating is a numerical indicator of the actual annual carbon dioxide emissions from the building. Typical performance would have an operational rating of 100. A building that resulted in zero CO_2 emissions would have an operational rating of zero, and a building that

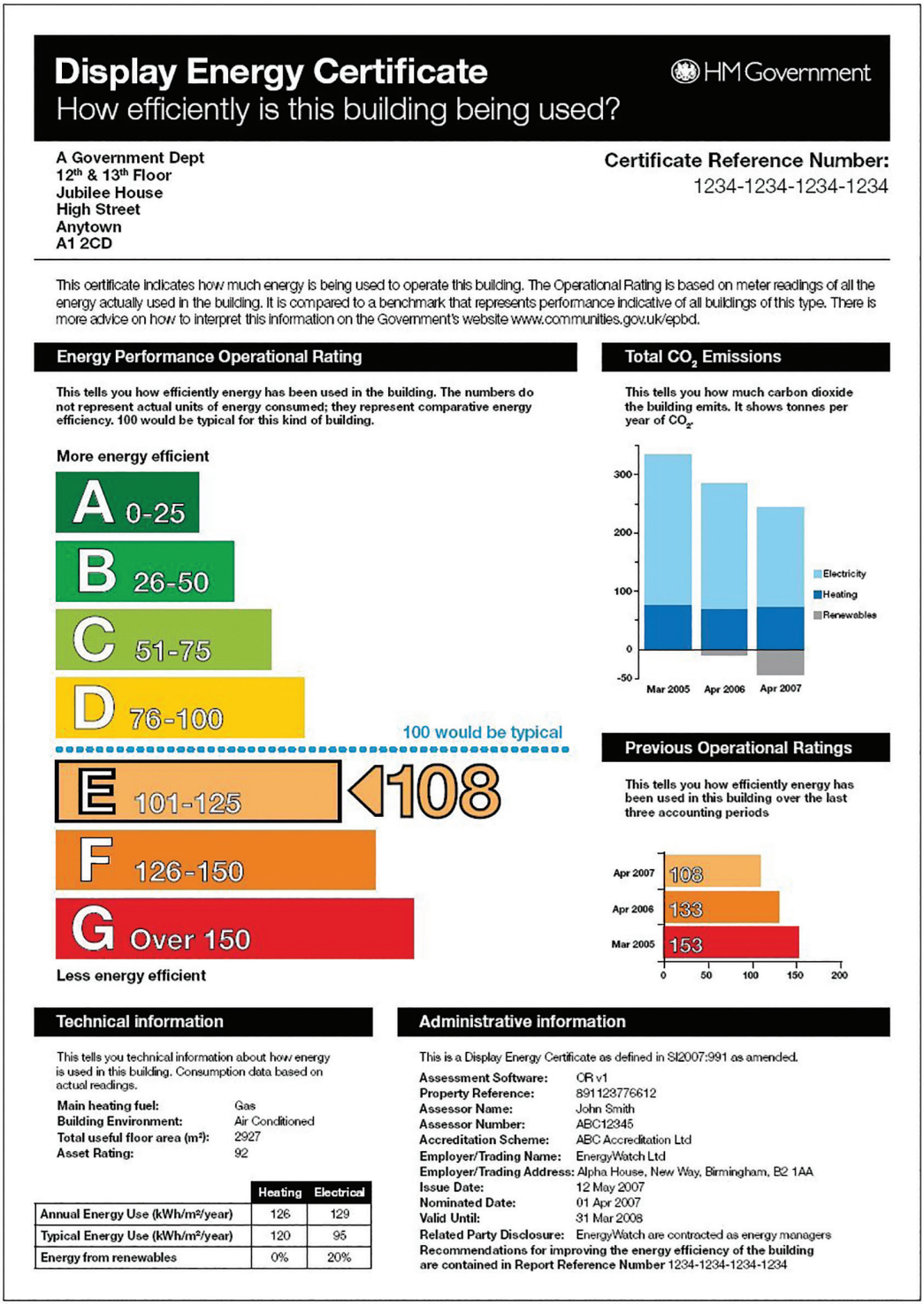


FIGURE 1.15 DEC for public buildings based on operational rating. (From https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/452481/DEC_Guidance__rev_July_2015_.pdf.)

resulted in twice the typical CO_2 emissions would have an operational rating of 200. If the building is a net energy generator, it would still be given an operational rating of zero (Department for Communities and Local Government, 2015). The United Kingdom has decided that the common unit should be CO_2 emissions, because this is a key driver for energy policy. This rating is shown on a scale from A to G, where A is the lowest CO_2 emissions (best) and G is the highest CO_2 emissions (worst). DECs for buildings >1,000 m² also show the operational ratings for the previous two years, where available (Department for Communities and Local Government, 2015).

In the United States, the most comprehensive plan to achieve carbon neutrality is the 2030 Challenge, which has been proposed by architecture 2030 and adopted by many organizations and cities. The 2030 Challenge requires all new buildings and renovations to be designed so as to currently reduce their fossil-fuel, GHG-emitting (CO_2) energy consumption by 70% below a Commercial Buildings Energy Consumption Survey (CBECS) building, increasing the reductions to 80% in 2020 and 90% in 2025 and achieving carbon neutrality by 2030. Architecture 2030 states that these targets should be accomplished by implementing innovative sustainable design strategies, generating on-site renewable power, and/or purchasing (20% maximum) renewable energy. Its goal is to achieve the necessary reduction in the global warming-causing GHG emissions of the building sector by changing the way buildings and developments are planned, designed, and constructed (http://www.architecture2030.org/).

Architecture 2030 has also developed the 2030 Palette and 2030 Districts. The 2030 Palette informs the planning and design process when ideas are being generated presenting sustainable planning, landscape, and building design principles and actions, called swatches, which provide location-specific strategies across the built environment through many locations and scales. The 2030 Palette selects examples of the best information and practices, and makes them intuitive and accessible. It is currently linked with climate consultant and plans are under way to link with other tools.

2030 Districts are private/public partnerships in urban areas across North America committed to reducing energy use, water use, and transportation emissions. The goal of 2030 Districts is to renovate existing buildings and construct high-performance infill development and redevelopment, bringing property owners and managers together with local governments, businesses, and community stakeholders.

1.7 CARBON-COUNTING TOOLS

Because GHG emissions can be used as a metric to measure and determine the effect of different sources on climate change, it is important to have the tools to calculate emissions from different sources. Several methods have been developed to do this.

The concept of carbon footprint has been defined in several ways but usually involves an estimate of the carbon dioxide emissions that an individual is directly responsible for over a given period of time (Padgett, Stenemann, Clarke, and Vanderbergh, 2008). Several carbon footprint calculators are available online to determine personal carbon emissions. These calculators can be used during the architectural design process and can provide a "feel" for the numeric relationships between lifestyle, consumption patterns, and emissions (Boake, 2010).

Other definitions of carbon footprint take life cycle analysis into effect. The Carbon Trust (2007) describes it as "… a methodology to estimate the total emission of GHGs in carbon equivalents from a product across its life cycle from the production of raw material used in its manufacture, to disposal of the finished product (excluding in-use emissions)."

Some authors (e.g., Wackernagel et al. 2005) see the carbon footprint as part of the ecological footprint (EF). However, they are different because the EF indicates a demand for resources and is expressed in units of area, hectares, or even planets. Although the EF developed by Rees and Wackernagel (Rees, 1992) measures how much bio-productive area (whether land or water) a population would require to sustainably produce using prevailing technology all the resources it consumes and to absorb the waste it generates, the carbon footprint is an emission—not a demand—and is measured in units of mass, not units of area.

Not only do carbon footprint calculators generate results in different units from carbon emission calculators (e.g., planets versus kilograms), but further complications also arise because there are GHGs with different GWPs. This is why CO_2e is used as a common unit of measurement that normalizes results and permits direct comparison between different sources and types of emissions. For example, emissions from water use can then be compared with emissions from energy used in the building, or embodied in its construction.

The first step to mitigate GHG emissions from buildings is to be able to count them. If carbon counting is integrated in the design process, the impact of architectural design strategies can be evaluated more easily to develop buildings with reduced emissions. To determine which of these could be easily used in the architectural design process, 40 GHG calculators and energy modeling software programs were compared in the main areas in which buildings are responsible for carbon emissions: operation, water, construction, and waste. Most carbon-counting tools offer the possibility of determining emissions from energy use in buildings or from transportation. Fewer of them can determine emissions due to water, waste, or construction. A handful of these even allows the calculation of the carbon impact generated from the food eaten in the building. Because many of these tools accounted for transportation, it was also included in this analysis (La Roche, 2010; La Roche and Campanella, 2009). These tools are compared in Section 1.8.

1.8 COMPARISON OF CARBON-COUNTING TOOLS

Several carbon-counting tools were compared to determine their performance and applicability. These tools can be used to convert the units obtained in different areas to a common unit of measure that would permit their comparison (CO_2e).

1.8.1 Selection of Carbon-Counting Tools

The 40 tools that were tested are listed in Figure 1.16. The first column lists the names of the tools, and the rest of the columns indicate the emission sources: operation, transportation, waste, construction, and water. A gray rectangle indicates that the tool can be used to calculate emissions from that source. Most of the tools calculate emissions from energy and some form of transportation (usually automobile or plane), but few of them account for emissions from waste, construction, or water. The full table with these tools is also posted on the Carbon-Neutral Design Studio Project website (http://www.tboake.com/carbon-aia/tools1.html) in the tools section. In addition to an image of a representative input and output screen, the table provides (1) the URL (2) the areas for which the tool calculates carbon emissions and each tool's subareas; (3) the ease of use on a three-point scale (easy, moderate, difficult); (4) the time needed to complete the information; (5) the units used in the output; and (6) general comments.

1.8.2 Comparing Emissions from Natural Gas and Electricity

To determine their precision, some of these tools were compared using the same input. Because many tools can calculate emissions from electricity and gas (Figure 1.16), several of these were compared by providing them with the same inputs and comparing their outputs. Only tools with the option to accept a similar input and to produce an output in the same units were selected for comparison. An annual consumption of 12,000 kWh was used as the input for electricity and 2,610 m^3 (921.6 therms) for natural gas. All of these calculators use site energy for their calculations, probably because it is easier to understand and provide input. A total of 14 calculators were compared, all of which generated different CO_2e values. For an input of 12,000 kWh, the emissions ranged from 2,673 to 8,182 kg CO_2e/year. The average was 5,286 kg CO_2e/year, or 0.44 kg CO_2e/kWh, ranging from 0.22 to 0.68 kg/kWh (Figure 1.17). As a reference, the average emission factor for grid electricity in the United States is 0.62 kg CO_2e/kWh (eGrid, 2007), and in the United Kingdom,

APPLICATION	OPERATION															TRANSPORTATION		WASTE	CONSTRUCTION	WATER
	ELECTRICITY	LIGHTS	FANS	A/C	APPLIANCES	NAT GAS	PROPANE	HEAT OIL	WOOD	COAL	LPG	KEROSENE	BUTANE	WATER HEATER	FURNACE	AUTO	AIRPLANE			
Act on CO_2 calculator	■	■				■	■	■		■	■									
American forests	■					■	■	■	■			■				■	■			
Athena: EcoCalculator for assemblies																			■	
Be green now						■									■	■	■			
Berkeley institute of the environment																				■
Best foot forward	■															■				
Bonneville environmental foundation	■					■	■	■								■	■			
BP calculator	■															■	■			
Build carbon neutral construction calculator																			■	
California carbon calculator	■															■	■			
Carbon footprint	■					■										■	■			■
CarbonCounter.org	■					■										■	■			
Carbon fund	■					■											■			
Center for alternative technologies	■					■										■	■			
Chuck wright	■					■		■								■	■			
City of fair Oaks, CA water use calculator																				■
City of Tampa, Florida water use calculator																				■
Clear water	■					■		■	■							■				
Electric power pollution calculator	■					■		■								■	■			
Energy star home energy yardstick	■					■	■	■												
Energy star target finder	■																			
EPA personal emissions calculator	■					■	■	■								■		■		
EPA waste reduction model WARM	■					■	■	■								■		■		
GEIC calculator				■	■										■					
HEED		■	■	■	■	■	■	■						■	■					
Home energy saver calculator		■	■	■	■									■	■					
Inconvenient truth	■					■									■					
Live neutral	■					■										■	■			
Pacific gas and electric	■					■										■				
Puretrust	■					■				■						■	■			
Resurgence	■					■	■	■		■	■		■							
Safeclimate	■					■	■	■		■	■	■				■	■			
TerraPass	■					■										■	■			
The conservation fund	■														■	■	■			
The nature conservancy's carbon footprint calculator	■														■	■	■	■		
Yahoo green calculator	■	■				■	■	■							■	■	■			
Water conservation calculator																				■
Zerofootprint: Earthhour	■					■	■	■	■			■				■	■			
Zerofootprint: Unilever Go Blue																				■

FIGURE 1.16 Carbon-counting tools.

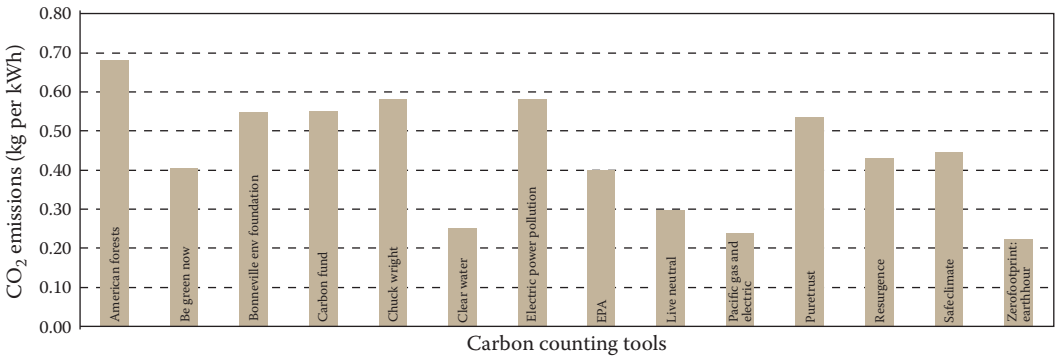


FIGURE 1.17 Conversion factor for electricity normalized in kg CO_2e/kWh for the 14 calculators.

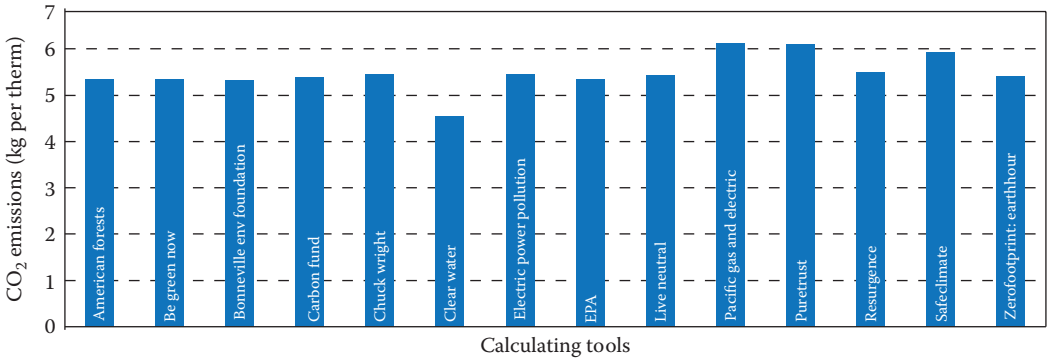


FIGURE 1.18 Conversion factor for natural gas normalized in kg CO_2e/therm of gas.

it was 0.43 kg CO_2e/kWh in 2005 (DEFRA, 2005) and 0.496 kg CO_2e/kWh in 2015 using the conversion factors for the CRC Energy Efficiency Scheme (2015) for grid supplied electricity. For on-site supplied, it is a bit lower (0.4585 kg CO_2e/kWh).

There was less variation in the calculations for natural gas. For an input of 2,610 m^3 of natural gas, the outputs ranged from 4,182 to 5,465 kg CO_2e/year. The average was 5,043 or 0.187 kg CO_2e/kWh (5.47 kg CO_2e/therm). The emissions range from 4.54 to 6.13 kg CO_2e/therm (Figure 1.18), and the average is relatively close to 5.43 kg CO_2e/therm (0.19 kg CO_2e/kWh), which is the fuel emission factor for natural gas proposed by Department for Environment Food and Rural Affairs (DEFRA) (2005) and later 0.1836 kg CO_2e/kWh in the table of conversion factors for the CRC Energy Efficiency Scheme (2015).

Unfortunately, most of these calculators are not transparent, and it is not easy to determine the calculation methods and conversion factors used by their engines, most of which probably implement very simple numerical operations. Even though this analysis was done several years ago, the variability in the results generated by the calculators demonstrates that it is better to determine appropriate site-specific conversion factors and to multiply this factor by the calculated or recorded energy used in the building. Several energy modeling tools are also incorporating the conversion factors for energy to carbon and the possibility for the user to adjust these factors.

These calculators provide a quick comparison and can be used as teaching tools, but for accuracy, it is probably better to use conversion factors from reputable sources to calculate GHG emissions. The United Kingdom's Department of Energy and Climate Change published the Table of Conversion Factors (Table 1.3) under the CRC Energy Efficiency Scheme (UK Department of Energy and Climate Change, 2015).

1.8.3 Recommended Carbon-Counting Tools

Based on the analysis of the tools, I selected several tools that could be used to count residential emissions and that are indicated in Table 1.4. At the time, when these tools were compared, there was no specific carbon-counting tool specifically designed for buildings. Many energy modeling tools are now incorporating carbon emissions in the results from their energy models. Some like green footstep (http://greenfootstep.org/), developed by the Rocky Mountain Institute, incorporates some of these features, but most of the calculations must still be performed outside of the tool itself. At this moment, the author is not aware of a tool that accurately integrates the calculations of emissions from different sources.

TABLE 1.4
Recommended Carbon-Counting Tools for Residential Building Design

Carbon Emissions	Tool
Operational energy	HEED (home energy efficient design) Provides separate results for heating, cooling, lights, appliances, fans, and water heater, enabling the designer to better determine the most effective strategy. Yearly energy results in the building energy performance screen can be multiplied by a conversion factor to obtain CO_2e or can be obtained directly from the program http://www2.aud.ucla.edu/energy-design-tools/
Construction	Build Carbon neutral Provides a very rough estimate. The total must be divided by the estimated life of the building to obtain CO_2e/year http://buildcarbonneutral.org/ or Athena EcoCalculator for Assemblies Provides a more detailed analysis but is not available for all regions http://www.athenasmi.org/tools/ecoCalculator/index.html
Water	The amount of energy embedded per unit of volume of water must be multiplied by the CO_2e conversion factors and the yearly building water use to obtain CO_2e A CO_2e factor per million gallons (1,331 lbs of CO_2e/MG) (0.002285 kg of CO_2e/L) was used (Southern California Factor). The water use in the building can be determined with many tools, for example, goblue.zerofootprint.net
Waste	EPA Personal Emissions Calculator (see the Waste section) for simple analysis permits the designer to model the effects of reducing home waste and recycling http://www.epa.gov/climatechange/emissions/ind_calculator.html EPA WARM model for a more detailed analysis: http://yosemite.epa.gov/oar/globalwarming.nsf/content/ActionsWasteWARM.html
Transportation	To obtain the emissions from transportation per household, the number of miles traveled per household is multiplied by the CO_2e factor per mile for that mode of transportation (train, bus, automobile). For example, for automobiles, the number of miles traveled is divided by the fuel efficiency of the automobiles and then multiplied by the emissions factor per gallon of fuel. Only automobile was considered with a factor of 2.32 kg of CO_2e/L, and a fuel efficiency of 9.36 km/L (19.56 lbs of CO_2 per gallon of gas and 22 miles per gallon) can be used. The number of miles traveled per year must be estimated and proposed

1.9 ADAPTATION, MITIGATION, AND RESILIENCE

These three concepts are important to understand the impact and responses to natural and human systems.

Vulnerability is the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. It is a function of the character, magnitude, and rate of climate change, and variation to which a system is exposed, its sensitivity, and its adaptive capacity (IPCC, 2007). It is affected by physical, social, and economic variables.

Adaptation is the set of initiatives and measures to reduce the vulnerability of natural and human systems against actual or expected climate change effects. Climate hazards must be understood to adapt to them, and exposure to these hazards must be reduced through the implementation of appropriate strategies. Adoption and implementation of adaptation measures avoid damage costs. Systems that have implemented appropriate measures will be less vulnerable to climate change effects.

Adaptive capacity includes all the capabilities, resources, and institutions of a city, country, or region to implement effective adaptation measures. In general, adaptation to climate change has not yet been sufficiently considered in most environments at all scales, leading to disastrous conditions when there are extreme climate effects such as heavy rainfalls, hurricanes, and heat waves.

The IPCC further defines various types of adaptation: anticipatory and reactive, private and public, and autonomous and planned. An example of adaptation is creating coastal dikes in response to rising levels in a river (IPCC, 2007). Adaptation is usually considered a short-term strategy by which we must prepare for system changes and reduce vulnerability.

There are three important terms that help define adaptation: coping range, resilience range, and failure range.

- *Coping range*: It is the magnitude of the disturbance that systems can tolerate without significant adverse impacts or the crossing of critical thresholds. These systems can be communities, enterprises, or ecosystems. A more resilient system has higher coping ranges.
- *Resilience range*: It is the magnitude of damage a system can tolerate, and still autonomously returns to its original state. Systems that have implemented several resilience measures will be more resilient and better resist the impact of a climate event.
- *Failure range*: It begins at the point where the magnitude of a damage is such that a system can no longer tolerate an effect without significant adverse impacts. Failure will occur when the climate hazard moves to the system beyond its resilience range.

The severity of an event in a system depends on the coping range and the resilience range. A system with no adaptation measures will fail sooner than a system that has implemented adaptation measures. Such a system will withstand more stress before it fails and has higher coping and resilience ranges compared to a system without adaptation measures. In a system such as this one, the coping and resiliency ranges increase and the failure range decreases. A system with adaptation measures in place will be more resilient to damage, in case a severe event takes place, and will also suffer less damage in an event with the same level of severity, compared to another system without adaptation measures. Figure 1.19 illustrates the coping, resilience, and failure ranges in a system with low and high resilience.

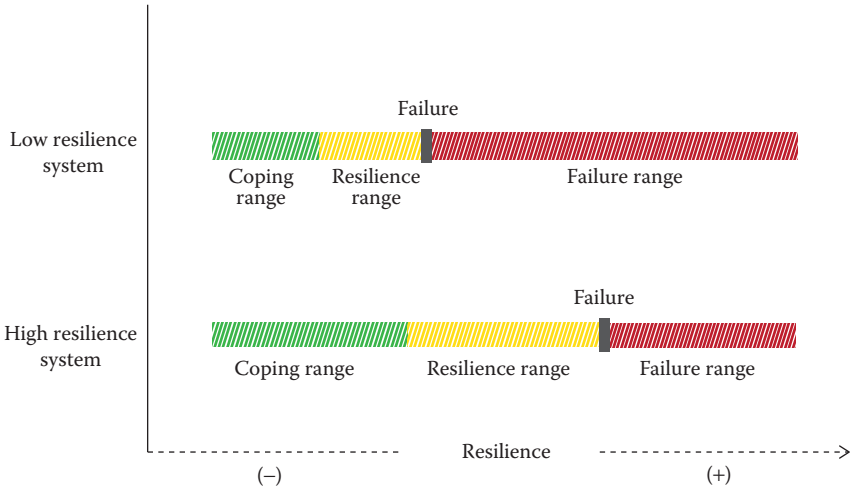


FIGURE 1.19 Effects of high and low resilience on coping and failure ranges.

Mitigation is a technological change and substitution that reduces resource inputs and emissions per unit of output. Several types of social, economic, and technological policies would help reduce GHG emissions and enhance sinks (IPCC, 2007). Some mitigation measures that reduce GHG emissions and sinks are: implementing energy conservation measures and increasing the use of low-carbon technologies. Another mechanism to mitigate the impacts of climate change is to enhance sinks that absorb CO_2, such as forests. To design effective mitigation strategies, it is important to understand available mitigation options, the role of technology, and market-based mechanisms.

Mitigation capacity in a country describes its ability to reduce anthropogenic GHG emissions or enhance natural sinks. The ability refers to skills, competencies, fitness, and proficiencies that a country has attained and depends on technology, institutions, wealth, equity, infrastructure, and information. Mitigation capacity is rooted in a country's sustainable development path (IPCC, 2007).

Both adaptation and mitigation are important and complementary to each other. Effective mitigation measures will reduce the impacts to which we will need to adapt, and effective adaptation measures will reduce the impacts associated with any given climate change effect. Both responses are equally important and can help reduce the risks of climate change to natural and human systems. Mitigation will have global benefits, whereas adaptation benefits are usually local or regional in scale. Adaptation benefits can be immediately visible in the region where they have been implemented, whereas the effects of mitigation are not always noticeable. Even with the most rigorous mitigation efforts, adaptation measures must continue to resolve immediate issues that will continue for many decades, even centuries. At the same time, mitigation is also necessary because if there was no mitigation, climate change would be of such a magnitude that effective adaptation would only be possible at very high social, environmental, and economic costs. Mitigation reduces the costs of adaptation.

A combination of strategies that include mitigation, adaptation, and technological development is necessary to reduce the risks associated with climate change. These synergies will also increase the cost-effectiveness of actions to tackle the impacts of climate change in several sectors such as agriculture, forestry, and urban infrastructure (Figure 1.20).

Resilience comes from the Latin word *resilio*, which means "to bounce back." Modern resilience theory usually dates to ecologist C.S. Holling's paper (1973) on the resilience of ecological systems. In ecology, the concept of resilience refers to a system's ability to respond to

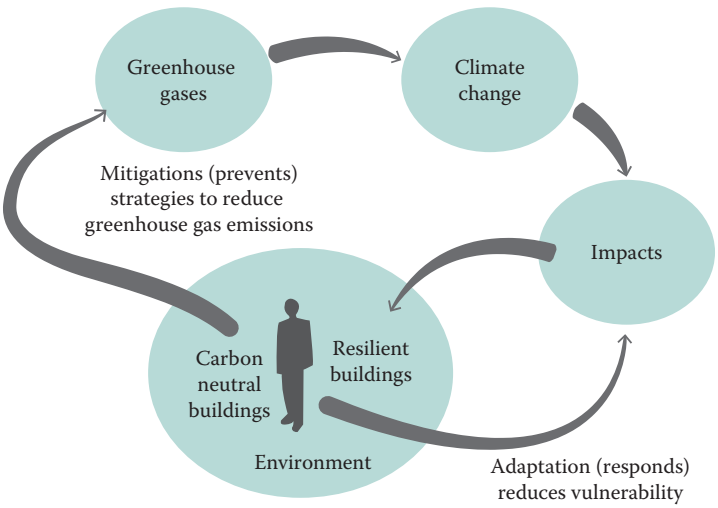


FIGURE 1.20 Mitigation, adaptation, resilience, and carbon-neutral buildings.

external shocks. Walker et al. (2004) define resilience as "the capacity of a system to absorb disturbance and reorganize while undergoing change, so as to still retain essentially the same function, structure, identity, and feedbacks." According to the IPCC, resilience is the ability of a social or ecological system to absorb disturbances while retaining the same basic structure and ways of functioning, the capacity for self-organization, and the capacity to adapt to stress and change (IPCC, 2007, Climate Change 2007: Synthesis Report). According to the resilient design institute, resilience is the capacity to adapt to changing conditions and to maintain or regain functionality and vitality in the face of stress or disturbance (http://www.resilientdesign.org/, extracted February 2016). The Resilient Design Institute (2016) also defines resilient design as "the intentional design of buildings, landscapes, communities, and regions in order to respond to natural and manmade disasters and disturbances—as well as long-term changes resulting from climate change—including sea level rise, increased frequency of heat waves, and regional drought." There are definitions for urban resilience in different subject areas: agricultural, engineering, environmental, and social sciences. After a literature review aided by bibliometric analysis, Meerow et al. (2016) propose a definition of urban resilience that includes six conceptual tensions that they found in other definitions, yet propose it in a way that it can remain flexible enough to be adopted by a range of disciplines and stakeholders. They define urban resilience as "the ability of an urban system-and all its constituent socio-ecological and socio-technical networks across temporal and spatial scales-to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity."

Specifically, urban resiliency refers to the ability of the cities, communities, or settlements to avoid collapse due to disturbances of many types such as food or gasoline shortages or earthquakes, floods, or hurricanes. There are three features that are central to a system's ability to reorganize itself aftershocks: diversity, modularity, and tightness of feedbacks. Diversity describes the number of elements in a particular system, and more elements create far more resilient systems. This diversity is expressed in the number of elements in the systems and the number of connections between these elements; more systems and connections make a system more resilient. For example, a city that depends on only one source of income is much less resilient to change than a city that has many sources of income. Modularity refers to the way in which the components that make up the system are linked (Walker and Salt, 2007). Modular systems are more independent and more specifically adapted to local conditions. Tightness of feedbacks describes how quickly and strongly the consequences of change in one part of the system are felt in other parts of the system. In smaller more localized systems, impacts are more apparent than in larger systems so that the members of the system have increased awareness and a shorter reaction time. Climate change is a good example of loose feedbacks. We are slow in reducing our emissions because in some locations, the effects of climate change are not yet apparent or are so small that they are hard to detect.

Urban resilience involves diverse stakeholders with different motivations. Therefore, resilience for whom, what, when, where, and why needs to be carefully considered (Meerow et al. 2016). It is clear that resilience is important and desirable for an urban system. However, if it is not possible to implement measures in all parts of the system, who determines the part of the system in which the measures will be implemented? Who determines what is desirable and for whom? Will the weakest and neediest continue to have less than those that have more resources? Who defines the critical areas and priorities? Different locations must be resilient to different factors, but how are these defined? Less developed countries and poor populations are the most vulnerable to climate change because they will have the least resources to implement adaptation strategies. A useful first step is to map areas that are vulnerable to climate change effects. Once these areas are mapped and the causes and impacts are determined, the appropriate mitigation strategies can be implemented.

According to the IPCC (2014), reducing basic service deficits, improving housing, and building resilient infrastructure systems could significantly reduce vulnerability and exposure in urban areas.

Urban adaptation benefits from effective multilevel urban risk governance, alignment of policies and incentives, strengthened local government and community adaptation capacity, synergies with the private sector, and appropriate financing and institutional development (*medium confidence*). Increased capacity, voice, and influence of low-income groups and vulnerable communities and their partnerships with local governments also benefit adaptation (IPCC, 2014).

2 Carbon-Neutral Architectural Design

To reduce anthropogenic emissions and have any real impact on climate change, it is necessary to reduce emissions from the building sector, and to do this, it is necessary to know how to reduce them. This can be achieved through a systematic process called the carbon-neutral architectural design process (CNDP).

As designers of the built environment, architects must know how to design carbon-neutral buildings. The knowledge to do this begins in architecture school, and this chapter discusses the CNDP, implemented by the author in architectural design studios in a professional program in architecture and projects in architectural practice. The objective of this CNDP is to help organize the steps and strategies in a design process that help to reduce building-related anthropogenic greenhouse gas (GHG) emissions. Many designers are aware of the impact of building operation on emissions, but as has already been mentioned, emissions can also originate during the fabrication of the building, from the supply of water to the building and from the disposal of waste from the building. Emissions from transportation are also affected by the building's location, so the consideration of neighborhood and local or regional planning issues is also important.

2.1 ARCHITECTURAL DESIGN PROCESS

2.1.1 Traditional Architectural Design Process

The architectural design process is intimately related to the process of problem solving, which in very general terms means that we need something but do not know exactly how to obtain it. The design process is also an iterative problem-solving process in which sequences of subproblems that are not well defined are solved. During the architectural design process, the documents to generate a building, which must satisfy many different criteria, are produced. Traditionally, this process begins with a series of diagrams and sketches that illustrate the architectural concept. These sketches are progressively refined with the addition of different criteria until the final proposal is developed.

Rittel (1970) proposed the existence of an alternating cycle, which repeats itself continuously in the design process. This process involves two types of mental activities: the generation and the reduction; between these cycles, there are periods of work with simple, routine activities in which the generation or reduction of ideas decreases in intensity. In general terms, during the generation stage, we propose alternatives, and during the reduction phase, we evaluate these alternatives. Thus, the architectural design process is a complicated one in which the architect generates and evaluates multiple solutions to finally produce a sufficiently refined object that fulfills the requirements of sometimes conflicting ideas or programs (Figure 2.1).

2.1.2 Computer-Aided Architectural Design Process

A computer-aided design (CAD) tool is a program or a set of computer tools that substitute for or add to traditional design tools used in the architectural design process. It can be any computer program that helps the architect solve an issue during the architectural design process. The ultimate objective of all CAD tools is to improve the product by improving the design process (La Roche, 1995).

The ideal computer design tool should be easy to use but precise so that it will have a larger base of users that will be able to generate a larger amount of buildings in a reduced amount of time.

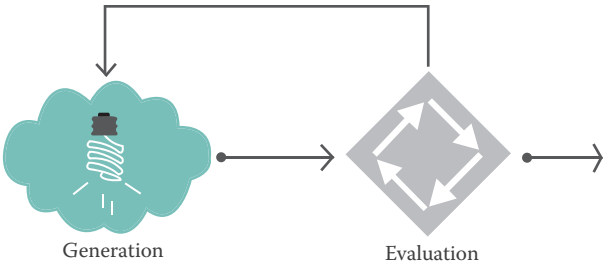


FIGURE 2.1 Alternating generation–evaluation cycle in the design process.

Very simple design (VSD) tools, proposed by La Roche and Liggett (2001), should be very easy and simple to use so that more designers can use them in more projects, which would improve the overall quality of a larger building stock. VSD tools should include a majority of the following properties:

1. *Easy to use*: They must have a graphical user interface and should provide results with a minimum amount of data, usually not more than six data inputs.
2. *Easy to learn*: Use of the tool should be intuitive so that the designer can be up and running quickly with it.
3. *Sufficiently precise*: The results should have sufficient precision to be useful during the initial stages of the architectural design process.
4. *Fast*: The process of inputting data and processing the information to generate results should not slow down the design process.
5. *Accessibility*: The tools should be free or very inexpensive so that they are available to a large number of users. The World Wide Web is especially useful as a sharing tool accessible to millions of users all over the world.
6. *Information exchange with other VSD tools*: The tools should permit the flow of information with other VSD tools to help maintain the continuity of the design process.

2.2 CARBON-NEUTRAL ARCHITECTURAL DESIGN PROCESS

Currently, there is no single tool available to calculate emissions from the building in all areas for an effective CNDP; however, a combination of methods, tools, and techniques can be used to achieve this. This section discusses a possible process to do this. The first step in this process is to generate a GHG emission baseline to be used as a reference, typically in kilograms of CO_2e per square meter per year (kg $CO_2e/m^2/yr$). In a CNDP, all data should be converted to a common metric. In addition to being carbon neutral, the building must also respond to the society's needs, as expressed in a program, budgetary constraints and code requirements, and environmental pressures to maintain healthy physical and biological environments. These pressures will continue during the development of the project, its construction, and its operation, and will affect it from the initial conception of the idea to its construction, operation, and demolition. During this process, the designer continually generates and evaluates ideas, compares them with the goals and the baseline, and adjusts them accordingly (Figure 2.2). The product of the design process is the project that provides the necessary documents for construction of the building. The project as designed should be predicted to perform better than the baseline and as close as possible to carbon neutral. After the project is concluded and in operation, postoccupancy evaluations and building audits will help to determine if the building is operating according to project predictions. Additional commissioning will be needed in most cases.

The goal of a CNDP is to design a zero emission building. This is difficult to achieve because it is not possible to eliminate all of a building's emissions. Energy and water will always be used, and some waste will always be produced (Figure 1.12). To achieve zero emissions, consumption must first be

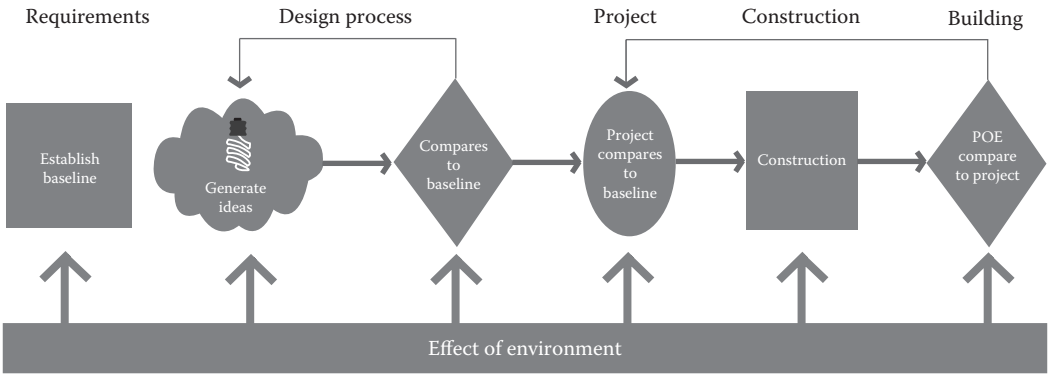


FIGURE 2.2 General phases in the carbon-neutral design project.

reduced as much as possible implementing appropriate design strategies, and then carbon sinks should be implemented to offset remaining emissions. These are not "sinks" in the traditional sense because they are not sequestering carbon but instead are offsetting equivalent amounts of CO_2e produced by other sources. A simple example is the use of renewable energy to offset emissions generated by a very low-energy building. A building is more or less "dirty" as a function of the magnitude of the emissions produced minus those offset by the sinks. A dirtier building emits more GHG than a cleaner building; a regenerative building goes a step further and absorbs more emissions than it produces, becoming a "sequesterer" of emissions. This building also absorbs the equivalent of the emissions produced during its construction and those produced by water use and generation of waste. A building can be an emitter or a sequester depending on the numerical relationships between the emissions from operation, waste, water, and construction (the latter distributed over the building's lifetime) and the magnitude of the carbon sinks. Figure 2.3 is a graphical representation of the different types of buildings loosely based on Equation 1.3. In this diagram, the horizontal axis represents the sum of all emissions. To the left of the *y*-axis are carbon sinks that offset emissions, and to the right are emissions generated by the

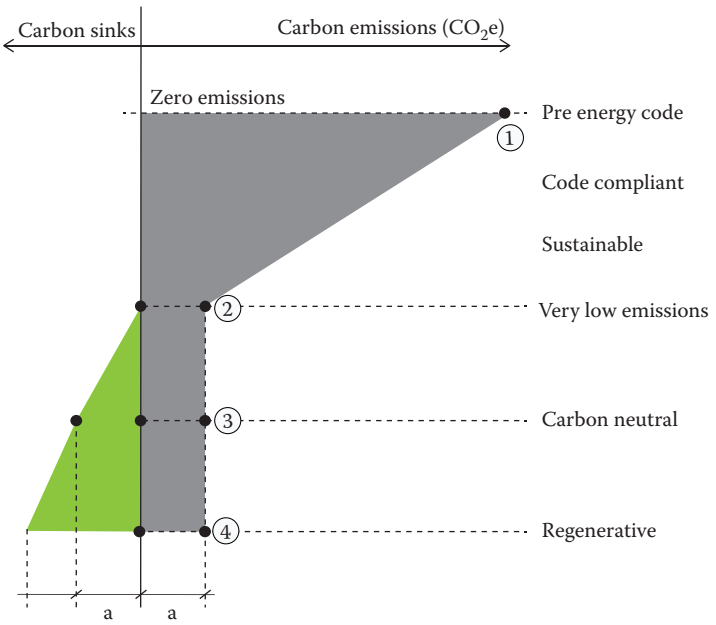


FIGURE 2.3 Building classification according to GHG emissions.

building. A building with more emissions has more area toward the right of the *y*-axis and a building with less emissions has more area to the left of the *y*-axis. Moving up and down the *y*-axis describes the different types of buildings according to their emissions. Higher emission buildings are higher in the *y*-axis and cleaner low emission buildings are toward the bottom. A high emission building uses much energy and water, is built with high embodied energy materials, and produces much waste without recycling much of it. High emission buildings will have more difficulty offsetting their emissions. A location far from public transportation also contributes to an increase in emissions to access the building; these emissions are not considered in this model.

There are several key points in this diagram: point (1) is a building that emits a large amount of GHG emissions and was probably built without any type of environmental considerations or complying with any energy code. A code-compliant building and a sustainable or "green" building are both lower in the *y*-axis with less emissions. As more carbon-reducing strategies are implemented, the building's emissions are gradually reduced. Point (2) is a building with very low emissions, in which multiple strategies have achieved maximum reductions with current technologies. Point (3) represents a carbon-neutral building in which the emissions to the right (in gray) are balanced with the sinks to the left in green (renewable energy, rain water harvesting, composting, wood construction); this is indicated by equal horizontal segments "a" on both sides of the *y*-axis. Any building below point (3) is regenerative because it is offsetting more emissions than it is generating. If a city or a neighborhood had more buildings below point (3), they would offset emissions from other buildings. Of course, if emissions from noncarbon-neutral buildings are lower, it would be easier to balance them to create zero emission neighborhoods.

To achieve these reductions, multiple strategies can be implemented in different areas and at multiple scales in a CNDP and illustrated in diagrams. Figure 2.4 illustrates a proposal developed by

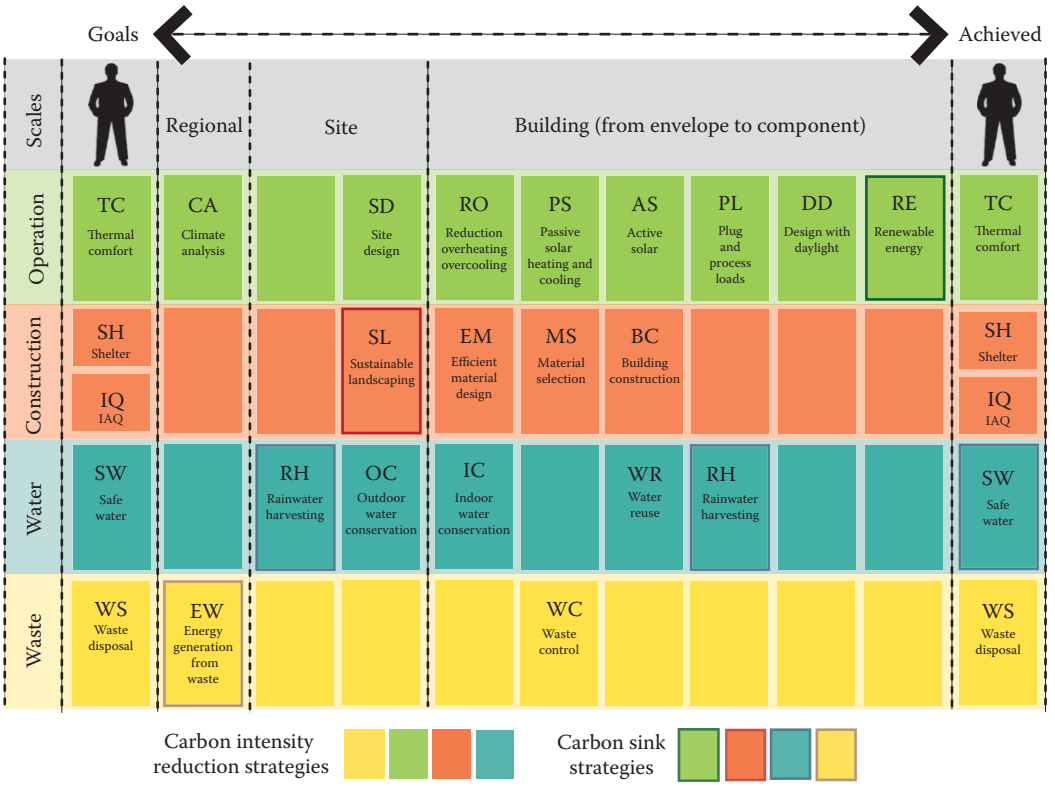


FIGURE 2.4 Carbon neutral design process.

the author and implemented in several carbon-neutral design studios at California State Polytechnic University (hereafter referred to as Cal Poly Pomona), Pomona, California, and in several architecture projects. This diagram is not static; it can and should be continually refined, updated, and adapted to specific conditions as needed.

In this diagram (Figure 2.4), the four horizontal bands are the sources of emissions previously discussed: operation, construction, water, and waste. The first column describes the baseline requirements for the different areas (operation, construction, water, and waste), and the final column describes what was actually achieved for each area, the outcomes. The columns between these two are roughly equivalent to scales in the process, from the regional–urban scale to the site, the building envelope, and finally the interior of the building. Different knowledge areas that discuss emission reduction strategies are located at the intersection of the columns and the bands, and are represented with colored rectangles. Some of these knowledge areas can reduce the carbon intensity of the building, whereas other knowledge areas can do the equivalent of absorbing the emissions, becoming carbon sinks and offsetting emissions generated in other areas. Knowledge areas that reduce the intensity of the carbon emissions are enclosed in rectangles, whereas carbon sinks have a thicker border around these rectangles. As previously explained, these carbon sinks are not the same as those described by climatologists and are closer to the definition of carbon offsets.

This book is organized following the structure of the diagram, indicating in each knowledge area the chapter that discusses it and providing information that can be used to reduce emissions in specific areas (Figure 2.5). These 10 chapters are not meant to be exhaustive references on each topic,

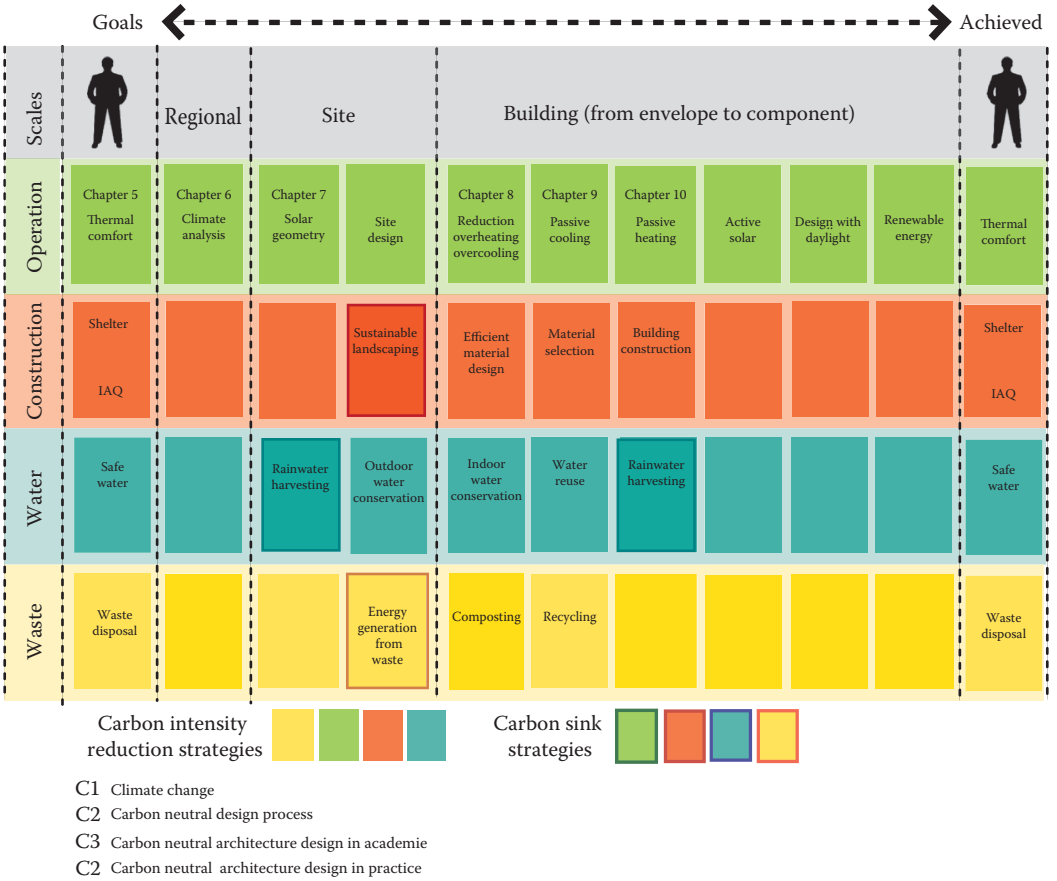


FIGURE 2.5 Carbon-neutral design process topics developed as chapters in this book.

but together they provide an overview of the knowledge necessary to design carbon-neutral buildings. For now emphasis is on emissions from operation, which can be responsible for somewhere between 60% and 80% of all GHG emissions originated over the life of the building.

2.3 URBAN AND NEIGHBORHOOD SCALE

Currently, almost four billion people, or more than half of the world's population, live in cities. Cities are the hubs of fossil fuel-based economic activity and emit >70% of global energy-related GHG emissions. According to the World Bank (2012), the world's 50 largest cities are collectively the third largest emitter of energy-related GHGs, after People's Republic of China and the United States. In many North American cities, transportation accounts for the largest share of emissions, whereas industry and buildings are the major sources in many Asian cities. The rate of urbanization is accelerating in many countries, with associated rapid and high-volume production of energy- and carbon-intensive building materials to construct an urban infrastructure.

According to the Intergovernmental Panel on Climate Change (IPCC), the impacts of climate change are already being experienced in cities, from severe storms damaging infrastructure, to droughts and floods, intensified heat waves, worsening smog, and other ecological and human health impacts. Many global risks for climate change are concentrated in urban areas (medium confidence). Steps that build resilience and enable sustainable development can accelerate successful climate change adaptation globally. Heat stress, extreme precipitation, inland and coastal flooding, landslides, air pollution, drought, and water scarcity pose risks in urban areas for people, assets, economies, and ecosystems (very high confidence). Risks are amplified for those lacking essential infrastructure and services or living in poor-quality housing and exposed areas (IPCC, 2014).

Four factors that directly affect building emissions at the urban scale are size, density, mix of uses, and layout. In general, because of the concentration of services, larger urban areas typically generate less emissions per capita than smaller urban areas. However, what might be a good size in a given location might be too large for another location. Population size alone gives a very incomplete picture which is better understood when density is factored in. Higher densities are usually considered more efficient because services can be used by more people, and there is a good ratio of services per capita. However, density also brings challenges. In dense urban areas, it is usually more difficult to produce solar energy because more buildings are blocking the sun and wind to each other, making it difficult to generate renewable energy to offset emissions. However, in these cases, it is also easier to use district systems or closed loop systems that benefit from the waste generated by a large population. There are also no ideal density solutions for all cities; denser cities benefit more by improvements in conservation and district-wide strategies, whereas cities with lower densities benefit more with renewable energy strategies such as solar because there is usually more rooftop space available per capita to capture solar energy. An increase in density with limited parks in a warm climate might accentuate the heat island effect, whereas this might not be as important in a colder climate. Because more people could live closer to where they work and to the services they need, mixed uses are typically helpful in reducing transportation emissions. Urban morphology and layout will also affect micro climates and solar impacts in buildings with related effects on thermal comfort and energy consumption, for example, solar neighborhoods in which the layout is designed to provide solar access for all buildings, which could be used for passive solar heating, solar hot water, and solar electrical.

The 2030 Palette (http://2030palette.org) is a simple-to-use tool that can be used to implement appropriate carbon-reducing design strategies for cities and towns. The proposed strategies (called swatches by the 2030 Palette) at this scale focus on design and planning practices that reduce the environmental impact of new and existing development. They include recommendations and rules of thumb for urban infill, retrofit, new growth strategies, open space and green infrastructure, and urban bikeways.

Even though it is helpful to use tools such as the 2030 Palette, it is important to understand that it is not enough to simply propose changes in density or layout, but the underlying systems must

also be understood to make the most appropriate decisions. These systems can be understood using an ecological approach (Williams, 2007). Williams proposes that the idea of community is central to ecology, and the materials and energies that constitute ecology create the form and pattern of the community, and these constituent elements are the characteristics of the community's scale and size. He continues to state that much of the current thinking in urban and community design focuses on the form of the neighborhood and the community. Projects have important goals such as walkable neighborhoods and small-scale streets that are good and can make for a charming community; however, if these systems rely only on nonrenewable energy, they are unsustainable. Any biological community, including the human community, must tie its long-term development and use to the sustainable energies and resources that are resident to the place. The systems and what is behind the form are also very important, and it is important to understand these in order to make less superficial design decisions.

The ecological model, when applied to urban and community design, guides the form of the urban pattern. Williams proposes several design elements that should be included for the region to remain healthy and compatible with human development:

- A bioclimate with compatible comfort zones
- Close proximity to other places, an ideal location
- A compelling sense of place and connection to nature and natural resources
- Buildable land and smart growth patterns
- Adequate precipitation
- Regional and local public transportation
- Productive soils and agriculture
- A diverse employment base as well as job creation capacity
- Planning to heal and reconnect natural system functions to urban patterns and green infrastructure needs

Strategies to achieve carbon neutrality at the urban or neighborhood scale are different from those to achieve it at the building scale. Roaf and Gupta (2006) proposed a set of useful strategies to reduce carbon emissions from cities and the necessary indicators to evaluate progress toward achieving these goals: *educational*—raising carbon awareness, solar education and training, and redissemination of best practices; *legal*—protecting solar rights, implementing building regulations, solar legislation for the electricity industry, or rate-based incentive schemes; *technical*—implementation of net metering, energy-rating schemes in buildings, and installed solar and energy-efficient systems; *policy*—rate-based incentive schemes and solar legislation for the electricity industry. These strategies provide a framework for a carbon reduction process and by their nature are more planning oriented than building-scale strategies.

2.4 BUILDING SCALE

The first part of the building design process is the site analysis that helps to define some external variables that will affect the building design. Climate and microclimate, vegetation, water, and topography are the key factors to consider. There are many publications that already discuss site analysis and design. This book will focus, in Chapter 6, on the effects of climate, sun, and wind, and the use of climate analysis tools and methods.

2.4.1 Operation and Energy

Operation emissions are generated during the production of energy necessary to operate the buildings. All of the knowledge areas listed here are included in the "operation" row and provide ideas and tools that can contribute to reduce these emissions:

Thermal comfort: Carbon-neutral buildings should provide healthy and thermally comfortable environments with minimum GHG emissions. A carbon-neutral building must achieve a certain level of comfort with a minimum amount of GHG emissions and environmental impact. Thermal comfort is discussed in Chapter 5.

Climate analysis: The analysis of the climate data where the building is located permits to propose design strategies that would help to achieve thermal comfort with minimum energy use in the building. Climate analysis is discussed in Chapter 6, and solar geometry is discussed in Chapter 7.

Site design: The environment directly around the building also affects a building's heat balance and can be designed to reduce emissions from operation, waste, and water.

Reduction of overheating and overcooling: This deals with the use of the building fabric to control energy flows to reduce summer overheating and winter overcooling. This is a necessary first step before implementing passive heating and cooling strategies or mechanical heating and cooling systems. Reduction of overheating and overcooling is discussed in Chapter 8.

Passive solar: A passive solar system uses the building fabric and materials to heat or cool the building. It is discussed in Chapter 9 (cooling) and Chapter 10 (heating).

Active solar: Active solar systems designate mechanical devices that collect solar energy in the form of heat and then store it for later use. The working fluid is usually water or air.

Design with daylight: Daylight reduces the use of electrical light and thus the use of electricity and the emissions associated with it. Furthermore, it provides many additional psychological benefits.

Renewable energy: Renewable energy is natural energy that is not limited in supply and will never run out. Using renewable energy can be considered a carbon sink because it offsets the use of nonrenewable energy.

Plug and process loads: It describes the energy used by appliances that are powered by means of an ordinary AC *plug* and that are not for general lighting, heating, ventilation, cooling, and water heating. The percentage of total building energy use from plug and process loads is increasing. Also as buildings become more efficient and use less energy, overall the percentage of energy consumption due to plug loads increases.

2.4.2 Construction

Emissions from construction can be produced during the fabrication of the materials used in the building, during the transportation of materials to the building, and during construction of the building.

Shelter: One of the basic goals of a building is to provide an appropriate shelter for the occupants and their activities.

Indoor air quality: Another fundamental goal is to provide healthy indoor environments.

Sustainable landscaping: A well-designed sustainable landscaping can absorb carbon emissions or reduce GHG emissions from the building. Landscaping can generate carbon emissions by the disturbance of the soil but can also act as a carbon sink (e.g., planting of rapid growth plants).

Efficient material design: It is used to design the building efficiently to reduce waste and optimize the use of materials (e.g., using modular design).

Material selection: Selection of low-energy, low-carbon materials is preferable because it is easier to offset when their emissions are low.

Building construction: Building construction can be optimized to reduce emissions from the flow of materials and people and to minimize waste and use of materials. Reuse of a building or part of a building will significantly reduce emissions from construction.

2.4.3 Water

Water consumption also generates GHG emissions during pumping and treatment from the source. The wastewater from the building must also be treated to remove physical, chemical, and biological contaminants, also generating emissions in this process.

Safe water: Provision of safe drinking water is a basic human requirement.
Rainwater harvesting: Rainwater harvesting is the capture and storage of rainwater to provide potable water for irrigation and drinking, or even to recharge the aquifer. It is considered a carbon sink because it offsets consumption of potable water, which not only is a very limited resource but also generates GHG emissions during the process to distribute to a building.

2.4.4 Waste

Solid waste (not transported in water) coming from the building must be transported away from the building and treated, generating emissions during the transportation. In addition, organic waste decomposing in the landfill will usually generate methane. If this methane is not harnessed as energy, it will escape to the atmosphere as a potent GHG.

Energy generation from waste: Methane tapped from a landfill can be used to generate energy. This energy is renewable as long as waste continues to accumulate and is offsetting emissions by using a GHG to generate energy and to reduce its effect on climate.
Composting: Composting is the purposeful aerobic biodegradation of organic matter into mostly organic material. Through composting, the amount of waste going out of the building is reduced. Emissions are also reduced because material that would otherwise decompose and generate methane absorbs this carbon and goes back to the ground.
Waste control: Waste prevention and recycling reduce GHGs by reducing the amount of new material that must be processed and the amount of material that goes back to the waste stream.

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3 Carbon-Neutral Architectural Design in Academia

Architectural education is a complex process that, in addition to traditional lectures, requires hands-on implementation of lecture material in studios so that the knowledge needed to reduce emissions is embedded in both lecture and studio courses. Introductory design studios provide the initial exposure of students to these concepts, lectures provide opportunities for in-depth learning of issues and concepts, and advanced topic studios and seminars provide opportunities to implement the concepts learned with more precision.

3.1 CARBON-NEUTRAL ARCHITECTURAL DESIGN PROCESS IN BEGINNING-YEAR STUDIOS

It is critical that environmental technology be taught at the introductory level, and the design studio is central to this learning process. If students are introduced to sustainability during the beginning years, these concepts can become an integral part of their design repertoire, and there are more opportunities for implementation in other projects during their architectural studies (La Roche, 2007). Undergraduate students in the Department of Architecture at Cal Poly Pomona are introduced to sustainable architectural design in the spring quarter of their second year in a set of required design studio and lecture courses, which are complemented by construction and history courses. In the lectures, sustainability is introduced with special emphasis on the control of natural forces: the sun and the wind. These concepts are incorporated in design projects in the studio portion of the course, and underscore an understanding of energy, the main "architectural factor" that affects climate change. At this introductory level, this is achieved by understanding shading, daylighting, and air movement in buildings, in addition to site design.

Because a designer has the capacity to simultaneously process only a limited number of pieces of information, it is important to reduce the number of issues that the designer, in this case the student, has to think about simultaneously, to a manageable amount, permitting to better resolve the issues. In most of these environmentally responsive studios, including the second-year studio, the importance of some design variables might be reduced to give more importance to sustainable design considerations.

Several diagrams were developed over different studios to illustrate the design process, which usually begins with an analysis at the urban scale or neighborhood and continues with the site analysis, the building envelope, and the interior of the building (Figure 3.1). Not all of these scales are always studied, and emphasis is placed on the building and its relationship with the site and environment around it. At the building scale, emphasis is on daylight and ventilation, again, at an introductory level. Students studied daylight with digital tools such as Ecotect and Sefaira or simple physical models and illuminance meters. Ventilation was studied with analog tools, such as a simple class-made wind tunnel or software such as Vasari, when it was available.

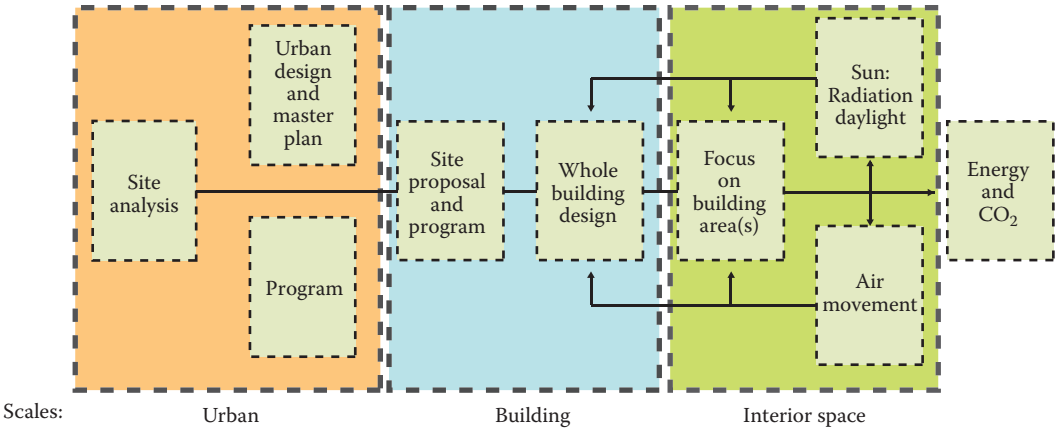


FIGURE 3.1 Example second-year design studio process involving multiple scales.

These analyses permit students to better understand the physical phenomena that affect thermal performance. Whenever possible, some analogue simulations, even if crude, are done before digital simulations. There are several reasons for doing analog before digital: (a) students should already have a sense of some of the physical phenomena before doing the digital work; (b) more information is required for the digital simulations; (c) some concepts cannot be calculated using analog simulation tools; and (d) in some cases, analog tools provide a more memorable effect that is easier to understand than a digital tool. However, it is sometimes easier to do changes and evaluate multiple options in a digital model making it easier to compare several "what if" scenarios. Figure 3.2 is an example of a simple student model analyzed with

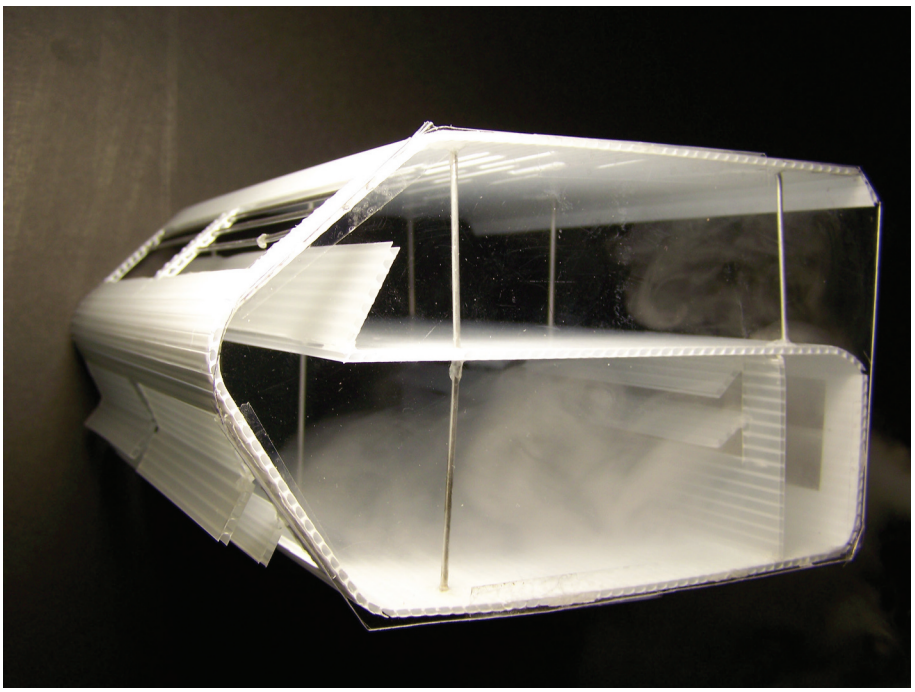


FIGURE 3.2 Airflow analysis with class-made wind tunnel. (Courtesy of Cal Poly Pomona students Calvin Mensonides and Emily Tragish.)

a "class"-made wind tunnel. Students can now access many energy modeling tools for free or at a very low cost.

As the student progresses through school, more digital analysis is done substituting the analog analysis. Furthermore, as students become more computer savvy and software more powerful, inexpensive, and easier to use, it is becoming easier and more common to use digital tools in the beginning design stages. However, the haptic value of physical models is difficult to beat with a flat computer screen, and some analogue simulations and testing are always recommended as learning tools.

Furthermore, in the second year it is not possible to teach sophisticated energy modeling tools because students lack sufficient building science knowledge to make appropriate decisions or use tools correctly. A strategy to gradually expose and introduce these tools and teach more complex problems is to only teach a specific portion of a program. For example, teaching them basic daylighting principles and then using the daylight module in Sefaira (previously we used Ecotect) to calculate daylight levels in their projects and requiring them to achieve a certain daylight autonomy. Students in more advanced topics studios used Ecotect, Radiance, Sefaira, COMFEN, and Diva, all of which provided useful results and were used directly in their studio projects.

Another diagram illustrating the carbon-neutral design process in the second-year architectural design studio was developed based on the topics usually discussed in class (Figure 3.3), when the author coordinated 2nd year studio. The diagram follows the same structure as the general carbon-neutral design process diagram explained in Chapter 2, but in this case, some of the general knowledge area rectangles now have additional rectangles inside them that

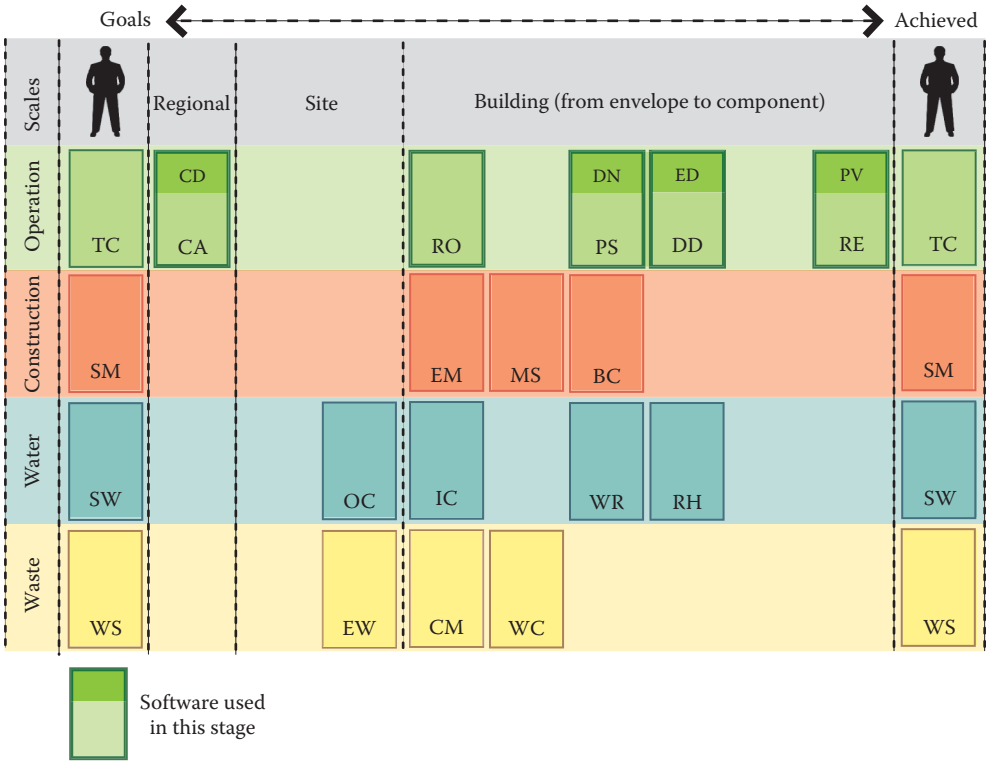


FIGURE 3.3 Example of carbon-neutral design process in second-year studio with implemented strategies.

represent specific strategies implemented in these areas of knowledge in the studio. Some areas are not implemented.

The areas in which digital tools are used are also indicated with a slightly thicker outline. Some of the tools that have been used are (1) Climate Consultant for climate analysis, (2) Home Energy Efficient Design (HEED) for energy modeling in residential projects, (3) Ecotect and Sefaira for daylight analysis, and (4) PVWatts for renewable energy.

As designers move forward in the development of their architectural projects, they implement several strategies shown in the diagram. The next paragraphs briefly discuss these strategies, which are also explained on the Carbon-Neutral Design Project site in the teaching section (http://tboake.com/carbon-aia/teaching/laroche/laroche.html).

Climate design (*CO*): Climate analysis consists of the survey of given climatic conditions to compare them with the requirements for human thermal comfort and to detect design opportunities that can be implemented to achieve comfort without the use of mechanical systems. Using climate analysis tools such as Climate Consultant (Milne, 2007) or Ecotect's Weather Tool, it is possible to propose building design strategies that can be implemented to achieve thermal comfort with reduced energy use. In some studios, traditional climate analysis was taken one step further to establish relationships between greenhouse gas (GHG) emissions and climate zones and to try to understand relationships between emissions and building location.

Low-energy envelope (*LE*): Design of the building envelope is critical because of its roles as a regulator of external conditions. Some projects were designed to operate only with passive systems, whereas other projects were combined mechanical heating with passive heating and cooling strategies. Students used HEED several times (Milne, Gomez, La Roche, and Morton, 2007) to determine energy use when mechanical systems were implemented and thermal comfort when only passive systems were used. It has been impossible to develop sophisticated energy models in a short 10-week quarter in which the students had to develop their design studio assignment balancing multiple factors.

Efficient daylight (*ED*): Students had to design fenestrations that achieved necessary illuminance levels inside their buildings while also minimizing glare. To achieve this, they performed daylighting analysis, initially with Ecotect with or without Radiance, and recently with Sefaira, which uses Radiance and local weather files instead of the CIE standard overcast sky that Ecotect used when not combined with Radiance. Figures 3.4 through 3.6 are examples of some second-year student projects only using Ecotect. Analysis helped students inform their design decisions.

Photovoltaic design (*PV*): After the building is designed with energy efficiency in mind, it is possible to generate much of the remaining electrical energy on site. Students calculated the total building load with HEED, and then used tools such as PVWatts to calculate and design the photovoltaic system, which was the most common type of renewable energy generated in their projects. Other forms of energy producing systems have also been explored by second-year students such as the bioreactor proposed by Hiba Charek for a visitor center in Joshua Tree National Park (Figure 3.7).

Integration of the systems in the project is important and emphasis has always been placed on the expressive possibilities of the systems. These systems improve building performance, but they must also be part of the architectural vocabulary of the building. Figures 3.8 through 3.10 show three student projects with three different styles, all in the same location, in a hot and dry climate and with similar systems. Formally the projects are quite different though they use many of the same systems. Students should understand that there is no such thing as a sustainable architecture style.

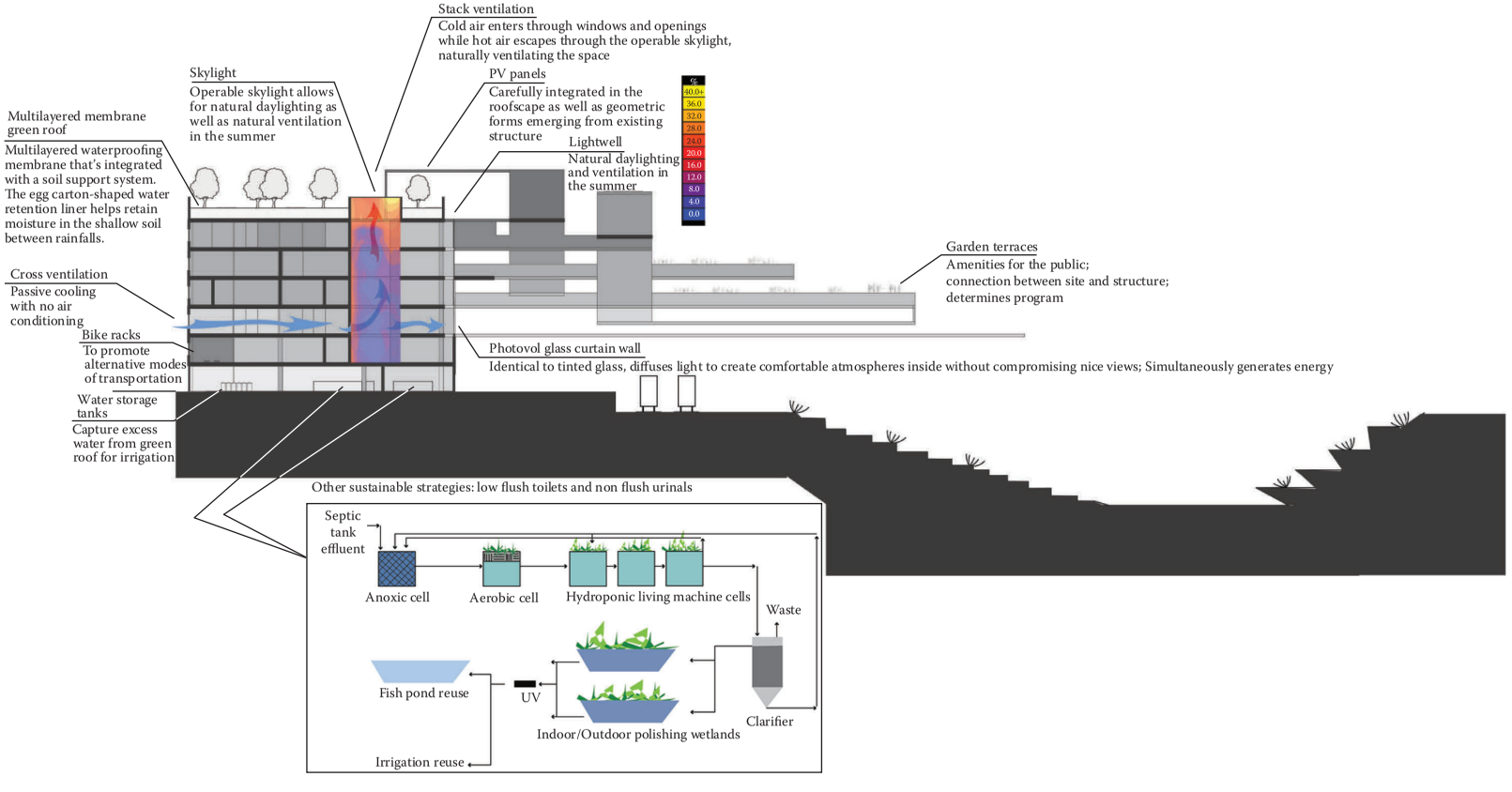


FIGURE 3.4 Daylight analysis in second-year student project. (Courtesy of Cal Poly Pomona students Kellene Kaas and Kenny Ngo.)

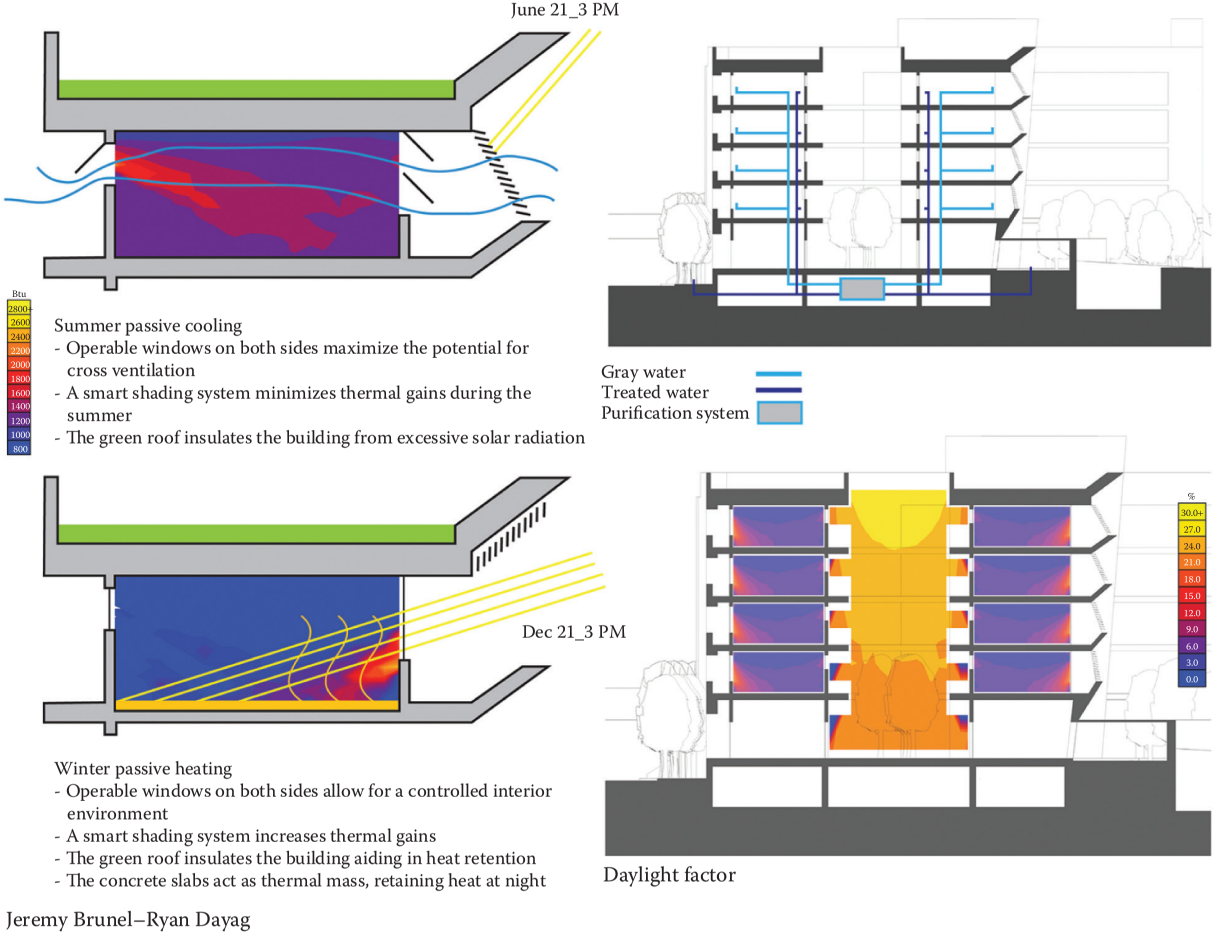


FIGURE 3.5 Daylight analysis in second-year student project. (Courtesy of Cal Poly Pomona students Sandeesh Sidhu and Greg Sagherian.)

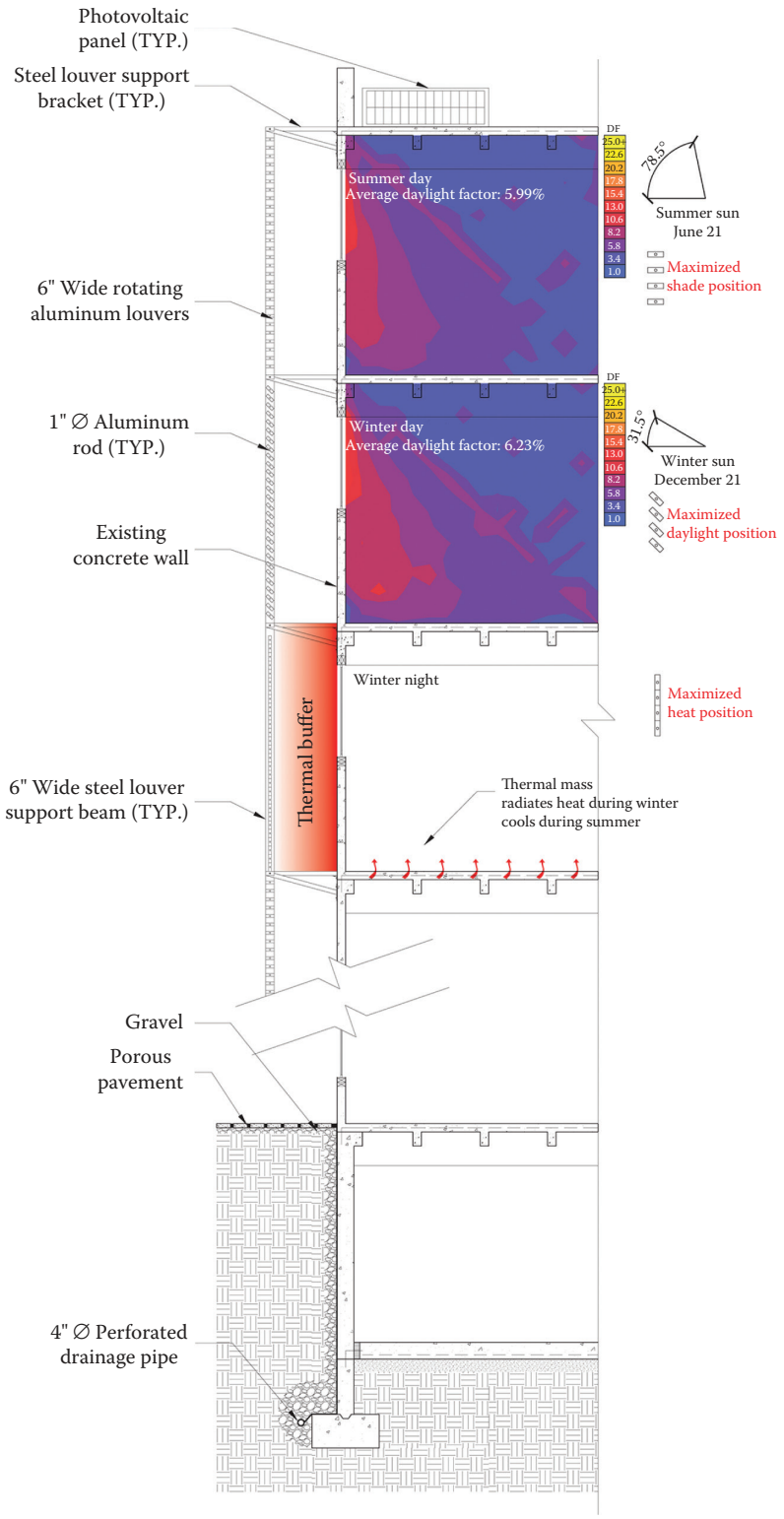


FIGURE 3.6 Daylight analysis in second-year student project. (Courtesy of Cal Poly Pomona students Jeremy Brunel and Ryan Dayag.)

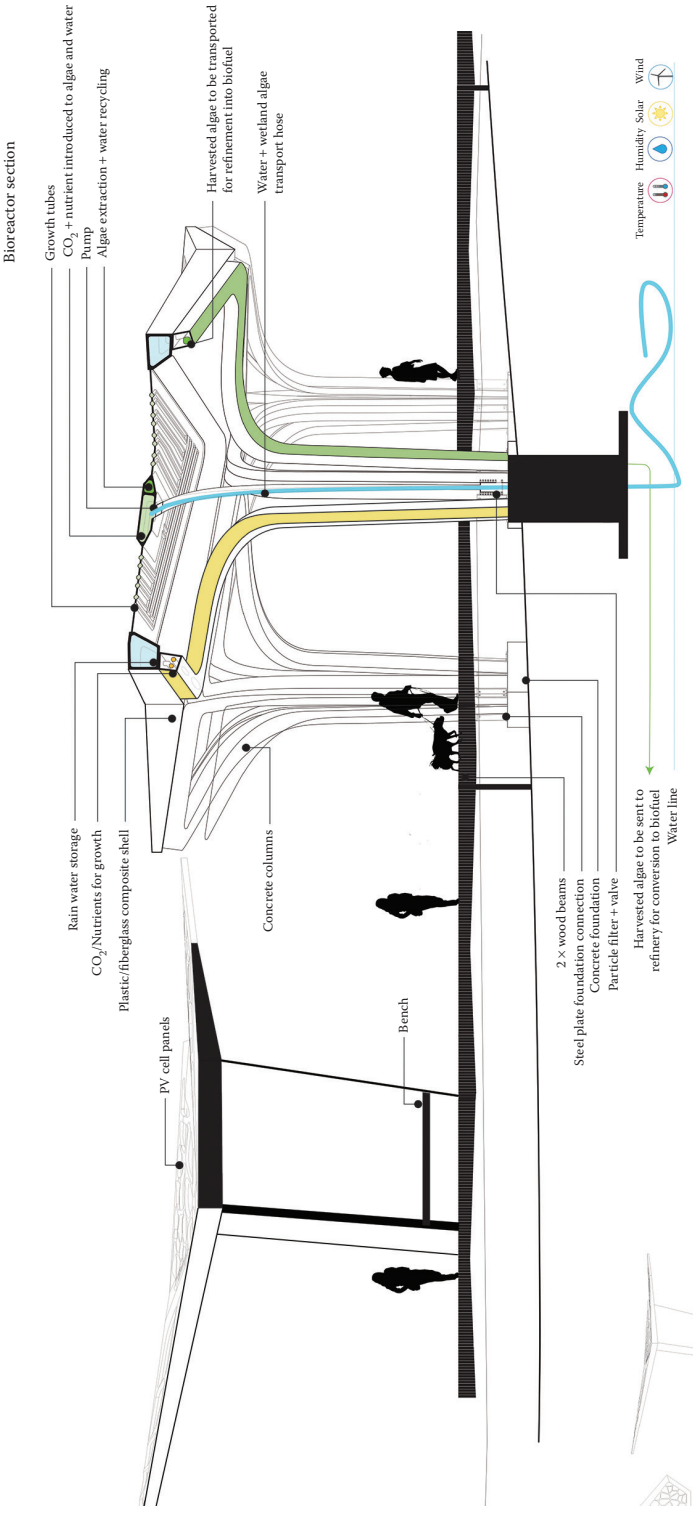


FIGURE 3.7 Bioreactor for Joshua Tree Visitor center. (Courtesy of Cal Poly Pomona student Hiba Charek.)

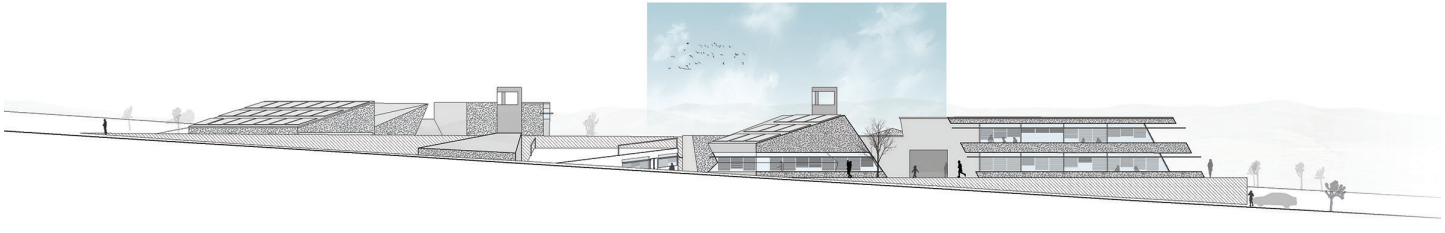


FIGURE 3.8 Visitor center in Joshua Tree. (Courtesy of Cal Poly Pomona second-year student Anna Budziyanska.)

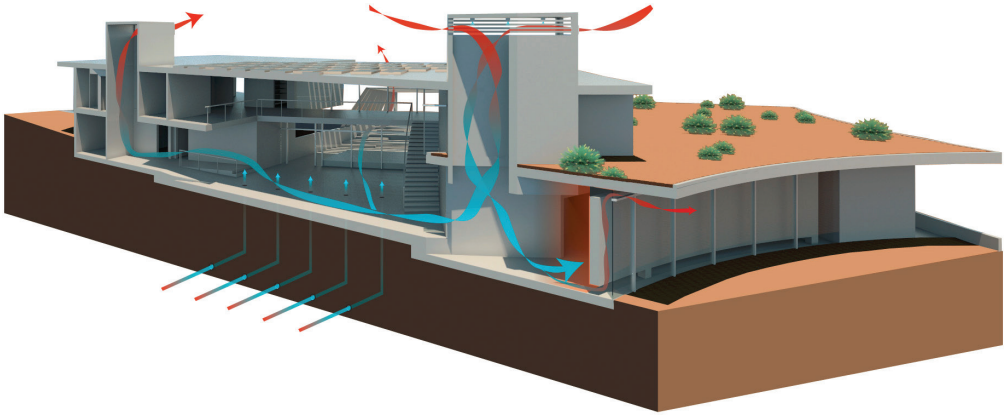


FIGURE 3.9 Visitor center in Joshua Tree. (Courtesy of Cal Poly Pomona second-year student Kevin Nicholson.)

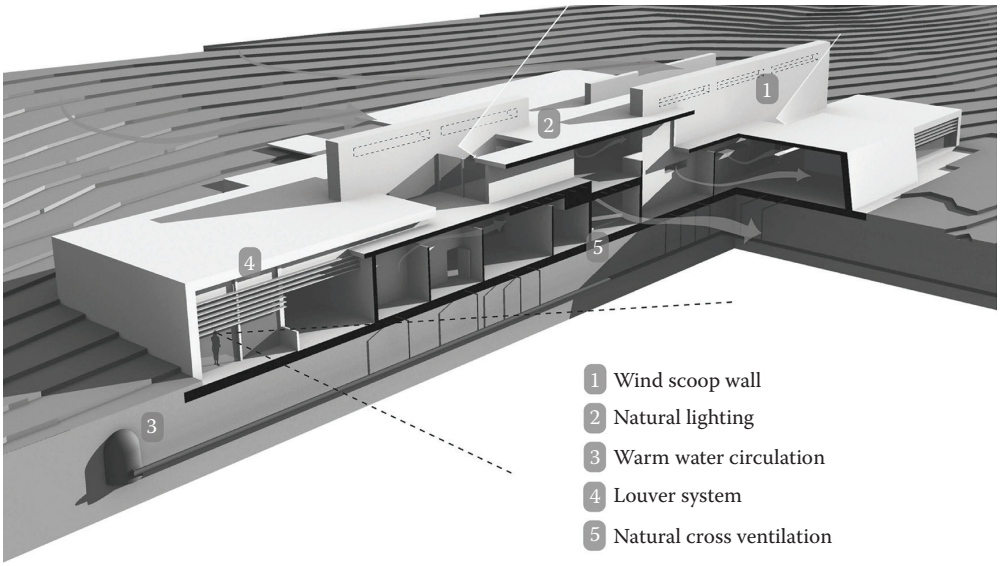


FIGURE 3.10 Visitor center in Joshua Tree. (Courtesy of Cal Poly Pomona second-year student Manny Zermeno.)

3.2 CARBON-NEUTRAL ARCHITECTURAL DESIGN PROCESS IN ADVANCED STUDIOS

The author has led several fourth- and fifth-year architectural design studios that explore methods and strategies to reduce the carbon footprint of buildings, and called carbon-neutral design studios or CND studios. This section describes, with examples from several courses, the process followed in these courses, which differs from that of beginning design studios. Some teaching strategies implemented in the studios are also explained in the teaching section of the Carbon Neutral Design Project website (www.aia.org/carbonneutraldesignproject), and some student projects are also posted on the website la2030studio.net.

In 2006, in the first of these CND studios, students developed low-carbon homes for different parts of the world as part of the GreenKit project funded by the EPA. Later in 2007, they proposed designs for carbon-neutral homes in two Southern California climate zones: the hot and arid desert and the

temperate coast. They developed low-energy buildings, integrating passive solar heating and cooling and renewable energy sources. In 2008 another studio focused on developing two low-cost carbon-neutral housing prototypes, the first for Pomona with Habitat for Humanity and the second one for Tijuana, Mexico, with a nonprofit organization, CORAZON. In 2009 the studio focused on affordable, sustainable, accessible housing for the U.S. Green Building Council (USGBC) competition in New Orleans, located in a hot and humid climate. Students had to design carbon-neutral buildings with improved energy performance, incorporating passive solar heating and cooling and renewable energy sources. They had to design an affordable single-family home that met the requirements of the USGBC's LEED for Homes Platinum-level certification and contained between 720 and 880 ft^2 of living space, for an elderly individual or couple in the Broadmoor neighborhood of New Orleans. The home had to be designed with this client in mind, as well as guests and future homebuyers.

The design studio in 2010 focused on the design of carbon-neutral cities (Figure 3.11), while in 2011, it focused on carbon-neutral buildings for several locations in western U.S. with special consideration to the relationship between water and energy in one studio and sustainable design for disaster relief in another studio. In 2012, the studio focused on the issues of Mexican border cities and students developed a community center for the city of Tecate. In 2013, the studio focused on a net-zero energy public fresh foods market and culinary school in the Bronx neighborhood in New York City that also addressed the neighborhood scale. In 2014, 2015 and 2017, students also continued exploring higher density solutions in downtown Los Angeles and in Seattle.

During the course of these studios, multiple exercises are developed at several scales, which involve the use of energy simulation tools and which will be discussed in the following sections. The exercises are organized in several steps that roughly correspond to traditional design scales: regional, neighborhood, site, and building (including the skin and interior spaces, Figure 3.12). Students in some cases also participated in a four-hour design charrette facilitated by Energy Design Resources (EDR), Southern California Edison that simulated a real-life professional environment with role playing. During the charrette, the students learned more about their roles as part of an interdisciplinary team in an integrated design process. This charrette was expanded by EDR to a 1½-day event open to all Southern California schools of architecture.

Students are first introduced to the design process that they will follow during the quarter and the tools that they will use to achieve low-carbon buildings. Again, a process diagram adapted from Figure 2.4 of the general carbon-neutral design process was developed (Figure 3.13). In this design, the strategies that were implemented are explained. More areas of knowledge can be proposed depending on the process, and many more strategies can be generated in each of these knowledge areas.

Climate design (*CO*): Climate design stands for climate-responsive design and is one of the main activities in climate analysis. Weather files are analyzed and compared to thermal comfort requirements, and appropriate climate-responsive design strategies are proposed. Climate Consultant or Ecotect's Weather Tool are two of the most commonly used analysis tools at this phase. Sometimes traditional climate analysis was taken one step further to try to understand relationships between GHG emissions and climate zones.

Geographical distribution of emissions (*GD*): Students are not used to visualizing quantities of CO_2, and it is important that just as they have already learned how to visualize their projects in dimensional units of measurement, they can also learn how to think in these units, understanding when a quantity is large or small. By quantifying the units in different climate zones, this exercise helps the students visualize units of CO_2 emitted per dwelling (Figure 3.14). The students determined annual residential CO_2 emissions for buildings according to their energy emissions and zip codes in different climate zones using a method developed in class with Home Energy Saver (http://hes.lbl.gov) and census tract information (http://census.gov). This exercise helped them understand relationships between carbon emissions, climate, and population density.

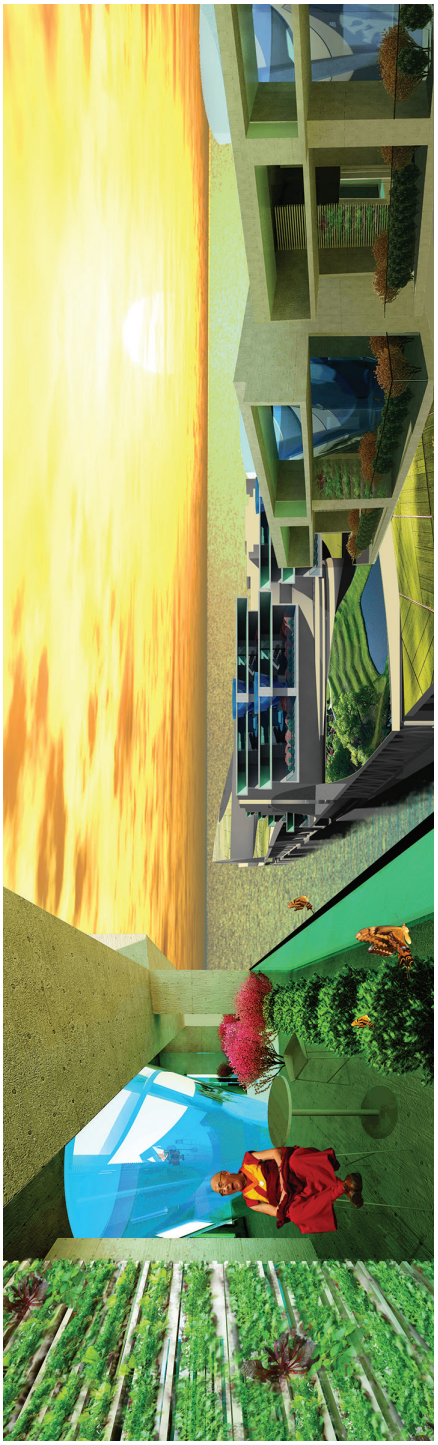


FIGURE 3.11 Oil platform city. (Courtesy of Cal Poly Pomona students Marcus Richeson, Alex Phung, Gabriela Barajas, and Ashi Martin.)

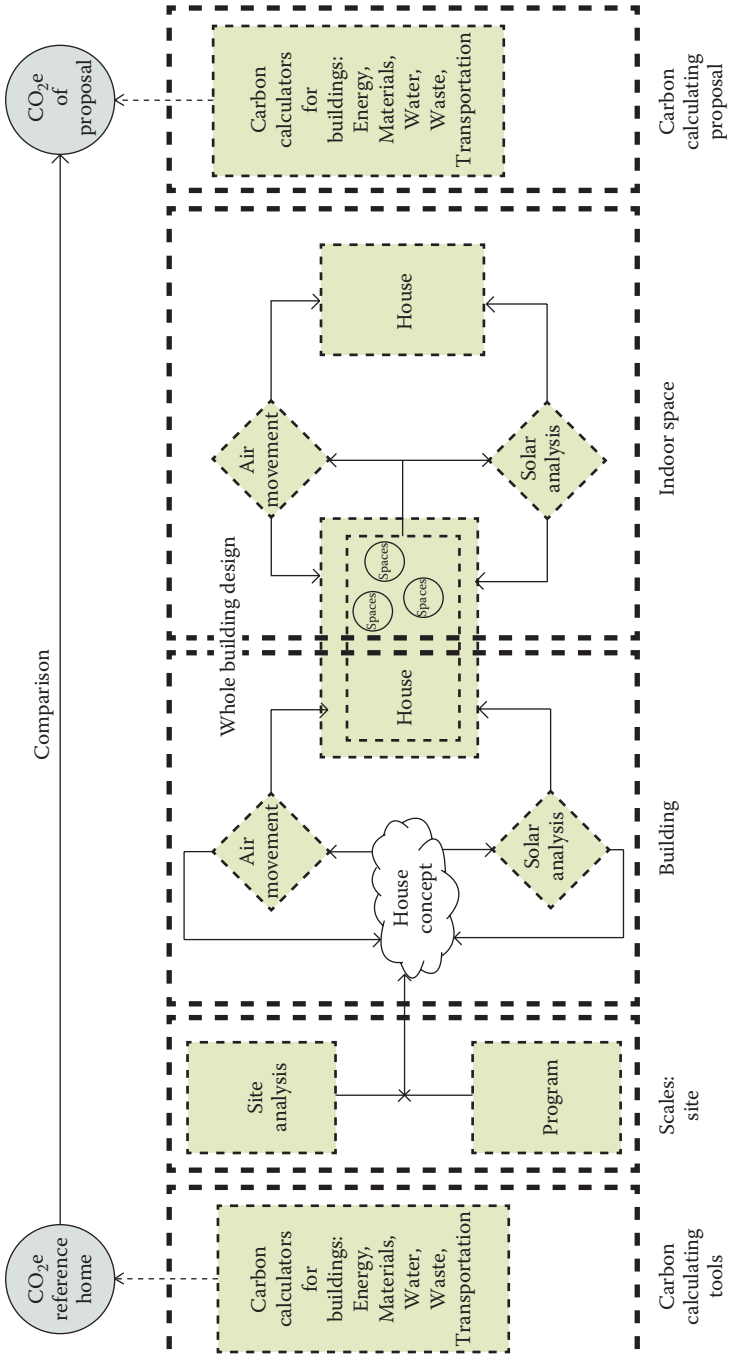


FIGURE 3.12 Example of a topic studio design process.

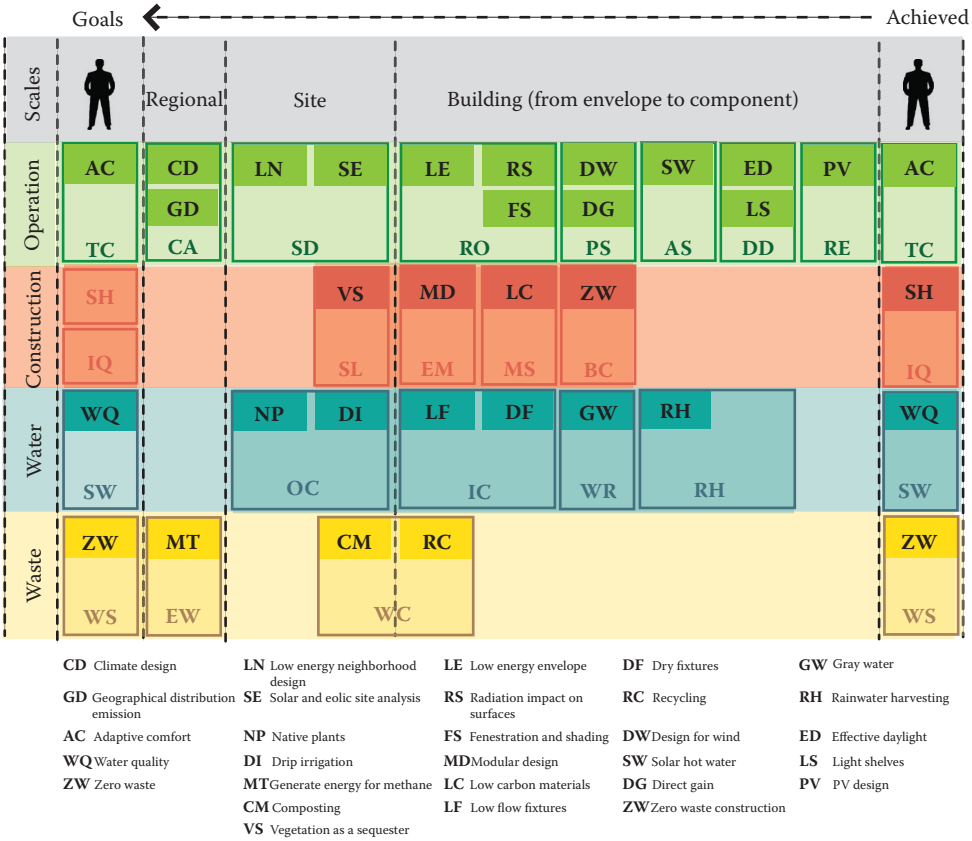


FIGURE 3.13 Typical carbon neutral design process implemented in advanced studios.

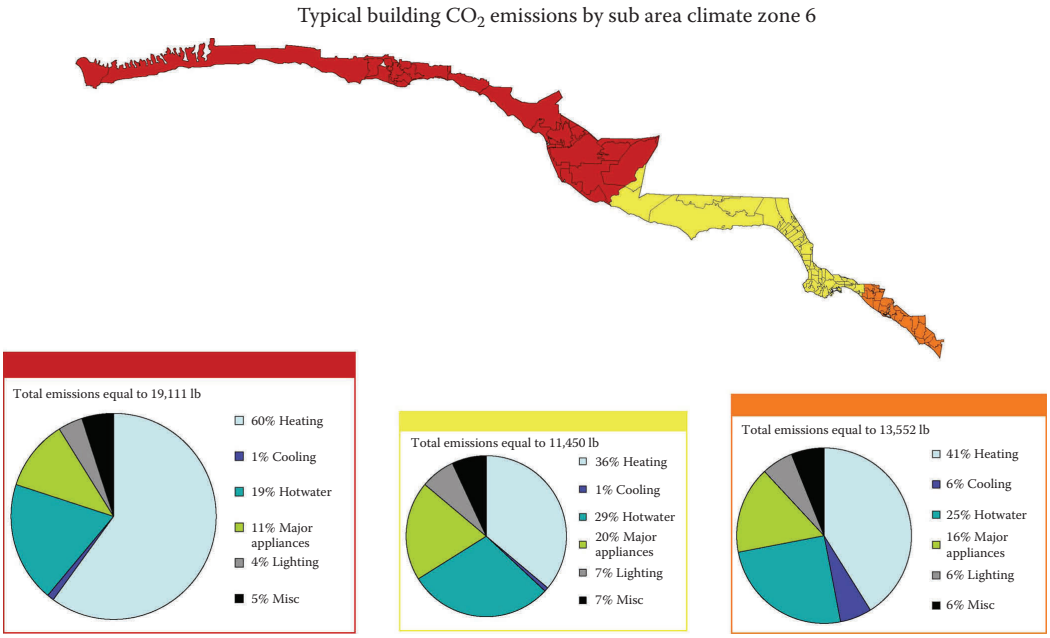


FIGURE 3.14 Geographical distribution of emissions in climate zone 6, California.

Solar and site analysis (*SE*): Building shading on outdoor spaces has an important effect on its perception and its use. If the outdoor space is intended for winter use and it is shaded by a neighboring building, it will probably be dark, cold, and unused. Nor will it be used if it is intended for use during hot weather and it is not shaded. Ecotect was used to generate sun path diagrams in different outdoor locations and determine the effect of building shading on exterior spaces and their potential during the summer or winter. Because they indicate when radiation will be available, these analyses can also be used to determine performance of PV systems or direct gain systems for passive and active heating. Adjustments in building massing can then be proposed to improve shading or solar access. Figure 3.15 shows how a group of students developed and tested shading options for a studio project in Palm Springs, CA. The sun path diagram shows, for specific locations, the shading effect of the proposed system. This type of solar studies is also commonly used to explore comfort in outdoor areas, by defining an overheated (summer) and underheated (winter) period. In the winter, solar radiation would usually be appropriate while in the summer it is better to block it, as shown in Figure 3.16 for the Bronx in New York City. Wind analysis has always been more difficult to simulate. Vasari provided a simple and free tool to understand the interaction

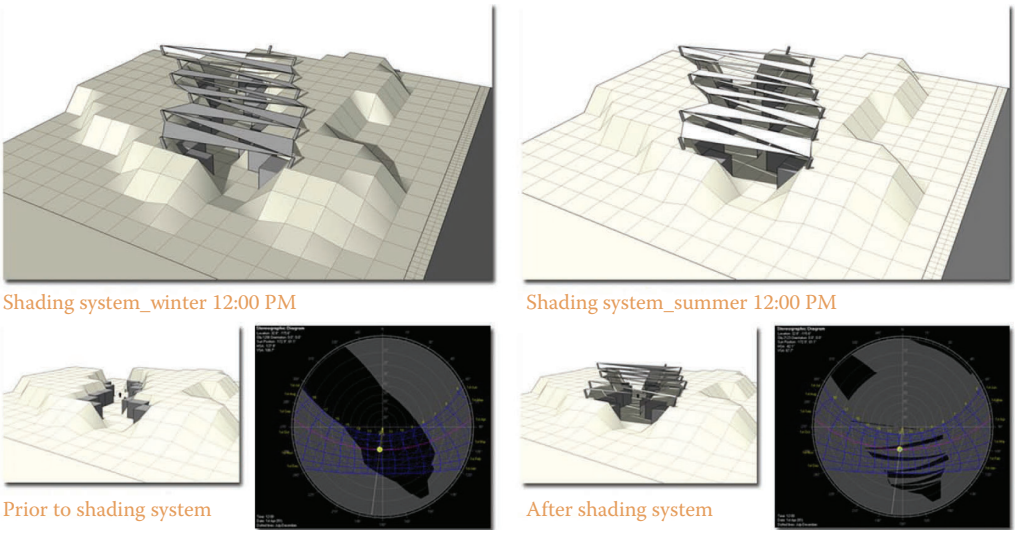


FIGURE 3.15 Solar and site analysis for a community in Palm Springs, California. (Courtesy of Cal Poly Pomona students Brandon Gullotti, Jon Gayomali, and Garret Van Leuween.)

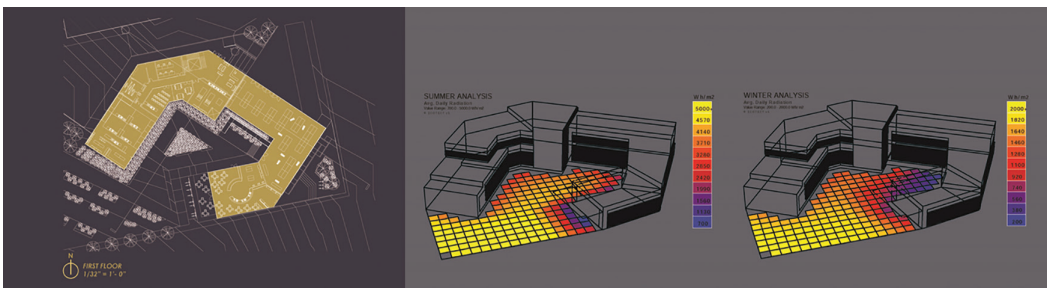


FIGURE 3.16 Solar analysis for a community center in Bronx, New York. (Courtesy of Cal Poly Pomona student Ben Gallardo.)

FIGURE 3.17 Wind analysis for a community center in Bronx, New York. (Courtesy of Cal Poly Pomona student Ben Gallardo).

between the buildings and wind direction and velocity. Figure 3.17 shows a student example in which the wind rose is used to determine dominant wind directions and speed which is then selected for analysis, in this case in Vasari, not available any more, but could also be in IESve. There are many ways to show the results of the site analysis, some of which can be very simple indicating fundamentals of solar geometry and wind direction (Figure 3.18).

Low-energy neighborhood design (*LN*): Students work in groups to propose a sustainable neighborhood plan in each climate zone, implementing concepts that would reduce the ecological footprint of the neighborhood and the city. These concepts include control of solar radiation and air movement, reduction of water use and resources, and community well-being. Figure 3.19 shows how the buildings are grouped to maximize southern exposure and how the sun path diagram is again used to analyze shading in three exterior locations at the site, while cross-ventilation is also promoted throughout the houses.

The state of California has suffered from insufficient water supply for the last several decades because a major portion of water comes from State Water Projects (SWP), which capture and

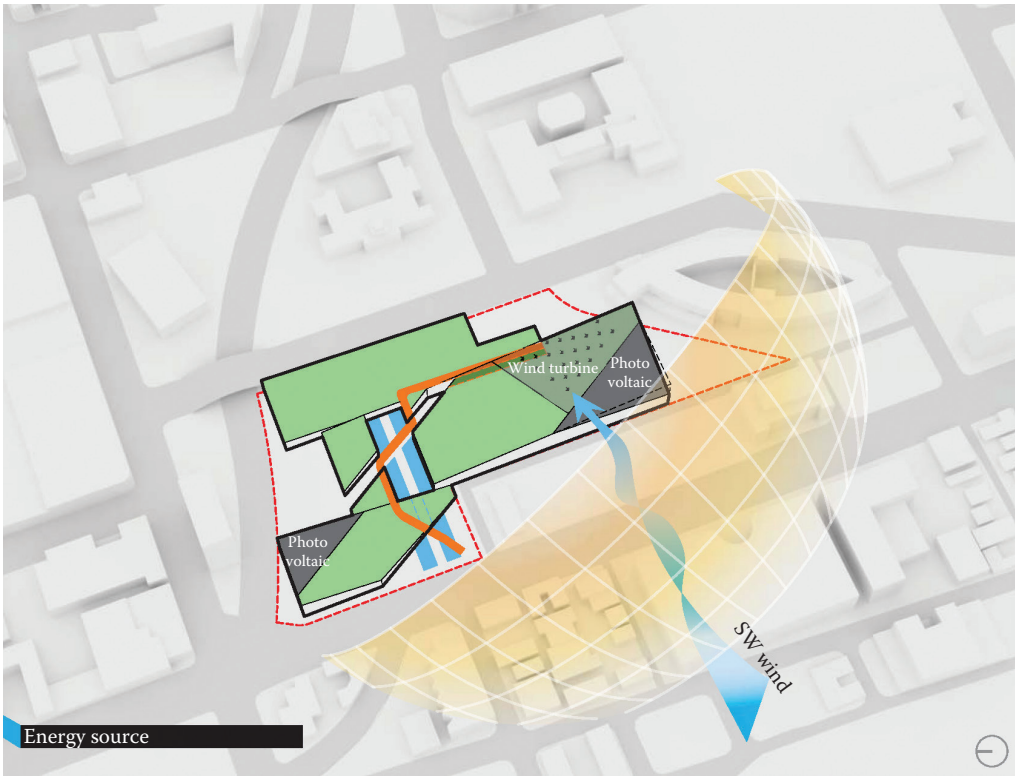


FIGURE 3.18 Simple site analysis diagram. (Courtesy of Cal Poly Pomona students Susan Han and Sul Han.)

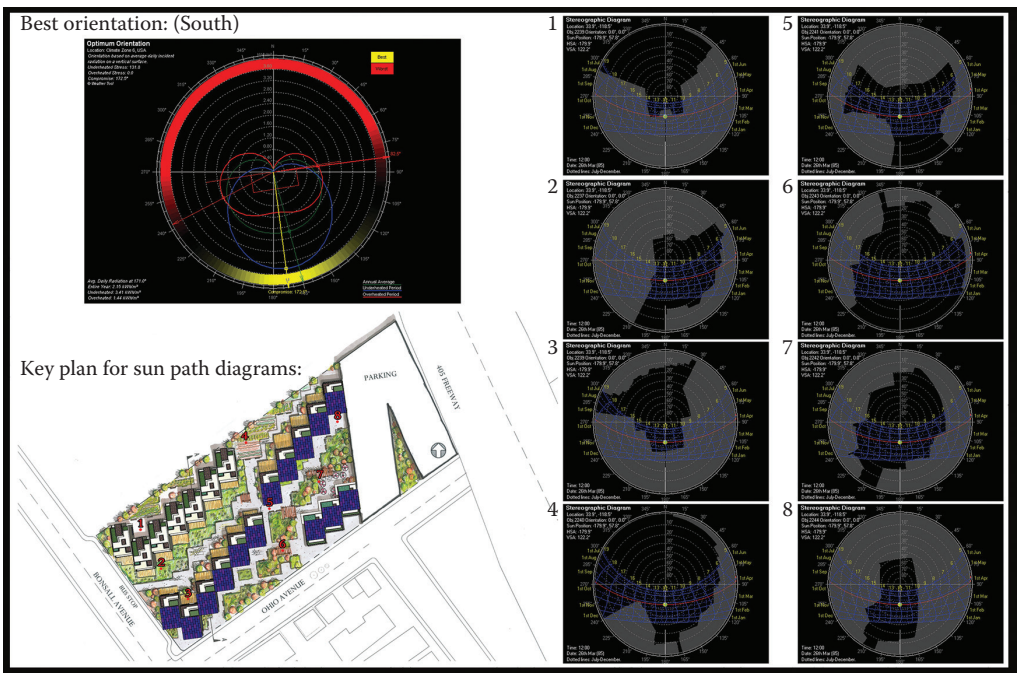


FIGURE 3.19 Solar and site analysis. (Courtesy of Cal Poly Pomona students Serge Mayer and Ryan Cook.)

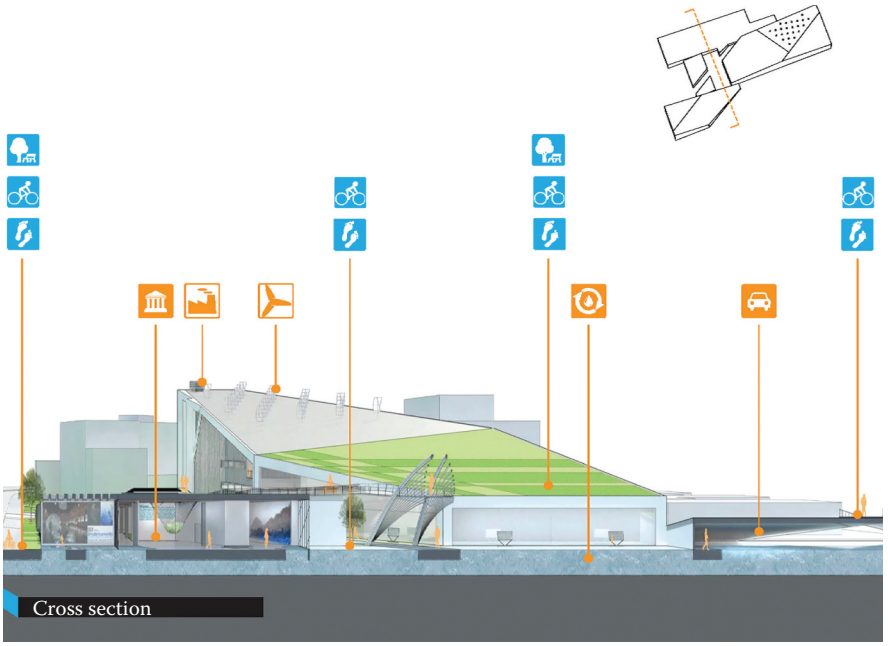


FIGURE 3.20 Site design infrastructure project in Santa Monica. (Courtesy of Cal Poly Pomona students Susan Han and Sul Han.)

delivers rain and snow runoff. Seventy-five percent of California's available water is imported from north of Sacramento, while about 80% of the demand is in the southern two-thirds of the state. As one of the solutions for the water crisis, California passed Proposition 50 that funds $50 million for brackish water and ocean water desalination projects. The Urban River Santa Monica project (URS) brings a desalination plant with reverse osmosis (RO) system into an urban and coastal city, Santa Monica, CA and attempts to utilize ocean water for both potable and nonpotable water (Figures 3.20 and 3.21). The main issue with the desalination plant and its RO system is the enormous amount of energy, which in the case of URS the students propose to solve utilizing renewable energies including Archimedes Wave Swing, photovoltaic panels, and in-house gasification of waste to energy. URS not only provides water to the city, but is also a park, an entertainment, and learning facility where families can spend their time. By taking the challenge of creating an inviting, family-friendly water desalination plant into an urban setting, students in this project standardize the future perspective of any type of plant. This idea is further pushed in the author's proposal for the city of Santa Monica in Chapter 4.

Figures 3.22 and 3.23 illustrate a student project for a multifamily project in Portland, Oregon with "community living rooms" to build connections between the neighbors, while looking out to views of Mount Hood, downtown, and Forest Park. The building provides a mix of scales, from the "big move" to the pedestrian, and has openings on multiple sides, providing a sense of space and belonging to the courtyards. The project incorporates multiple passive strategies combined with renewable energy integrated in the facade and a ground source heat pump as the mechanical system. Figures 3.24 and 3.25, also for the same location, show other student examples that include a strategies diagram and chicken coops and a bike path all the way to the top floor, acknowledging the importance of both for the people of Portland.

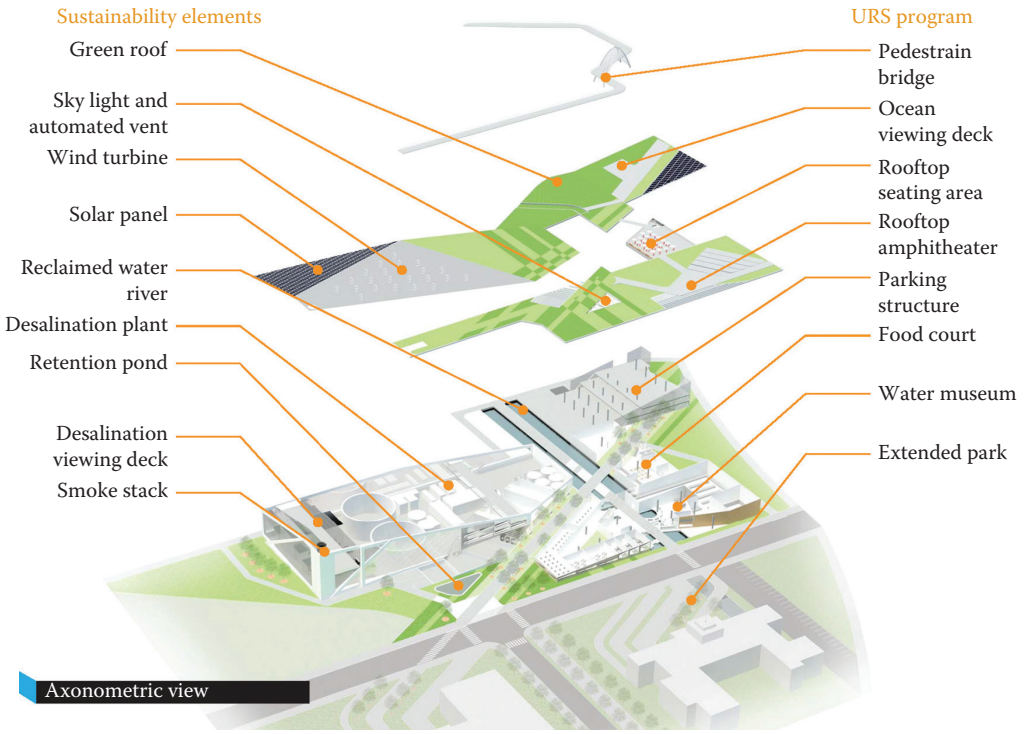


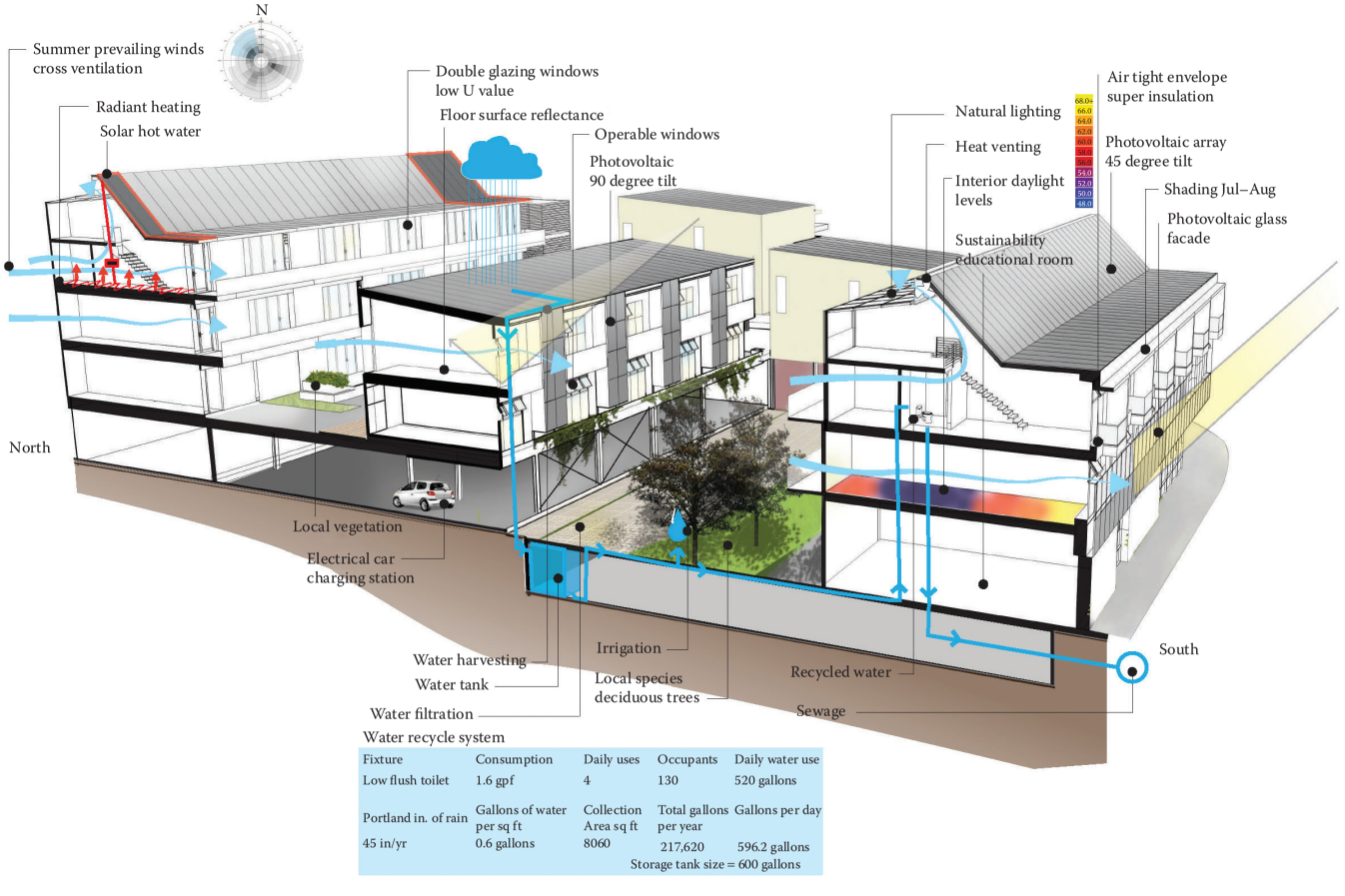
FIGURE 3.21 Infrastructure project in Santa Monica. (Courtesy of Cal Poly Pomona students Susan Han and Sul Han.)

Neighborhood design was also an important consideration in the 2014 senior project studios. The creation of the Los Angeles 2030 district as an interdisciplinary public–private collaborative provided an opportunity for this studio to develop a carbon reduction plan. Students developed a GHG inventory that included energy use and energy embodied in buildings, transportation, waste, and water use. More than accuracy of results, it was important that the students understood that establishing a baseline and comparing progress and results to this baseline were important parts of the process.

Inspired by the decarbonization plan for Chicago (http://smithgill.com/work/chicago_decarb/), students proposed an integrated approach to reduce district carbon emissions while creating an environment with economic and cultural vitality. Based on the inventory that reflected the different sources of emissions (energy, waste, water, construction, and transportation), they proposed strategies in five broad groups, following the same categories as in the Chicago plan: city image, smart infrastructure (water, energy, waste), mobility, buildings, and community engagement. Students analyzed existing nodes, paths, edges, districts, and landmarks to propose a plan that builds on these and improves readability of the downtown district, increasing pedestrian connections through greenways and networks of parks and open spaces. A 24-7 community was proposed by promoting mixed use development and an increase in density and in the number of amenities for those who would live in the district. A geothermal system using sewer lines as a heat sink with two separate closed loop systems would provide district heating and cooling. Water retention on-site is maximized, controlling urban

FIGURE 3.22 Multifamily project in Portland Oregon. (Courtesy of Cal Poly Pomona student Eduardo Gandara.)

FIGURE 3.23 Multifamily project in Portland Oregon. (Courtesy of Cal Poly Pomona student Eduardo Gandara.)



Fixture	Consumption	Daily uses	Occupants	Daily water use
Low flush toilet	1.6 gpf	4	130	520 gallons
Portland in. of rain	Gallons of water per sq ft	Collection Area sq ft	Total gallons per year	Gallons per day
45 in/yr	0.6 gallons	8060	217,620	596.2 gallons
			Storage tank size = 600 gallons	

FIGURE 3.24 Multifamily project in Portland Oregon. (Courtesy of Mario A. Gonzalez.)

FIGURE 3.25 Multifamily project in Portland Oregon. (Courtesy of Jessica Radparvar, Alejandra Ramirez.)

runoff through permeable pavements and strategic location of green roofs. Three collecting plants were placed in the district to promote recycling, while a waste vacuum collecting system would improve street sanitation, while reducing operation and maintenance costs. On-site electrical generation with PV and wind systems improves the performance of the electrical grid and reduces transmission losses. Parking structures are moved to the edge of the district and would include a network of solar-powered buses that move people through the district. Bicycle paths and bike stations in addition to the pedestrian network provide additional transportation options with many intermodal possibilities close to the metro and commuter train stations (Figure 3.26). Building strategies focus on envelope retrofits that improve thermal performance, combined with passive heating and cooling strategies to reduce energy consumption and increasing daylight. Building integrated photovoltaics and wind turbines provide clean energy options that would meet about 90% of the peak demand. The community education plan

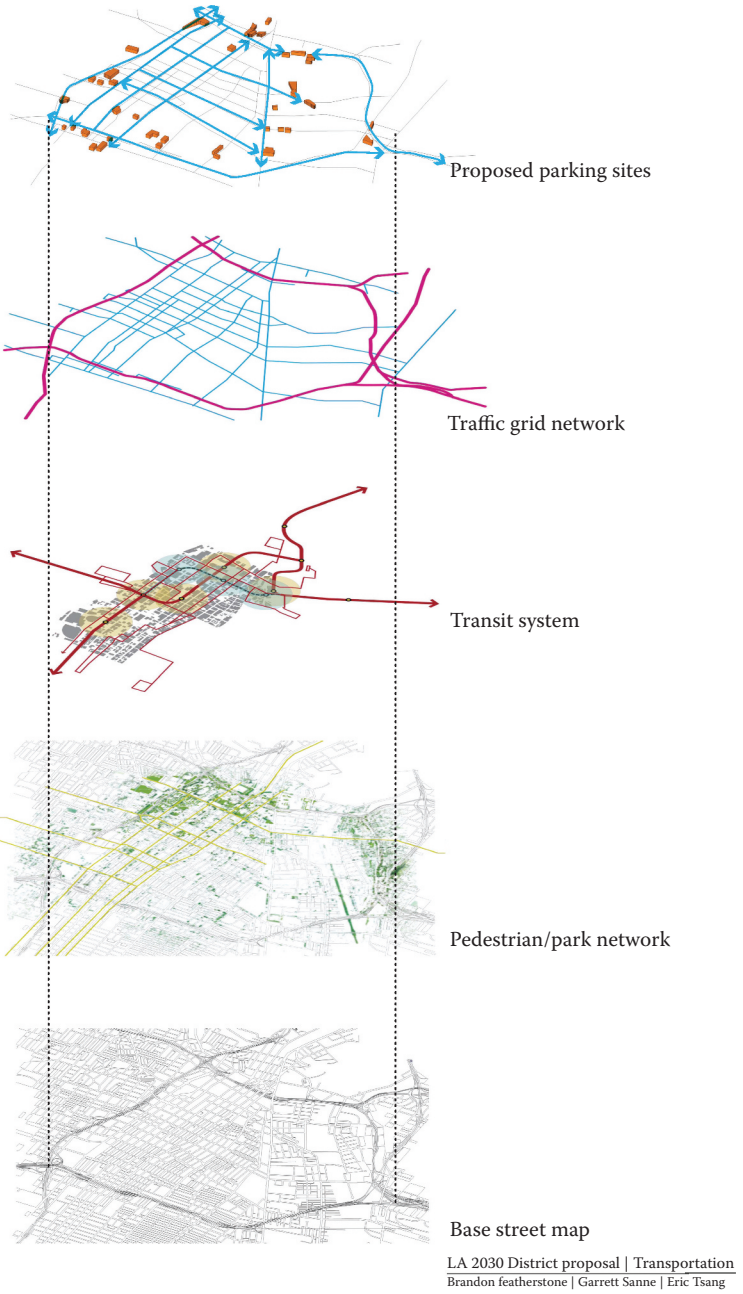


FIGURE 3.26 Mobility proposal for Los Angeles 2030 district. (Courtesy of Cal Poly Pomona students.)

proposes a "hands-on" approach to learning that includes public art in parks and urban spaces, streets, pedestrian routes, and bus stops. Sustainability is also integrated in school curricula in neighboring magnet schools, interactive social media, and community while school gardens combined with workshops educate both children and adults on eating and living sustainably (La Roche, 2014). Figure 3.27 shows the results of the initial analysis and urban proposal.

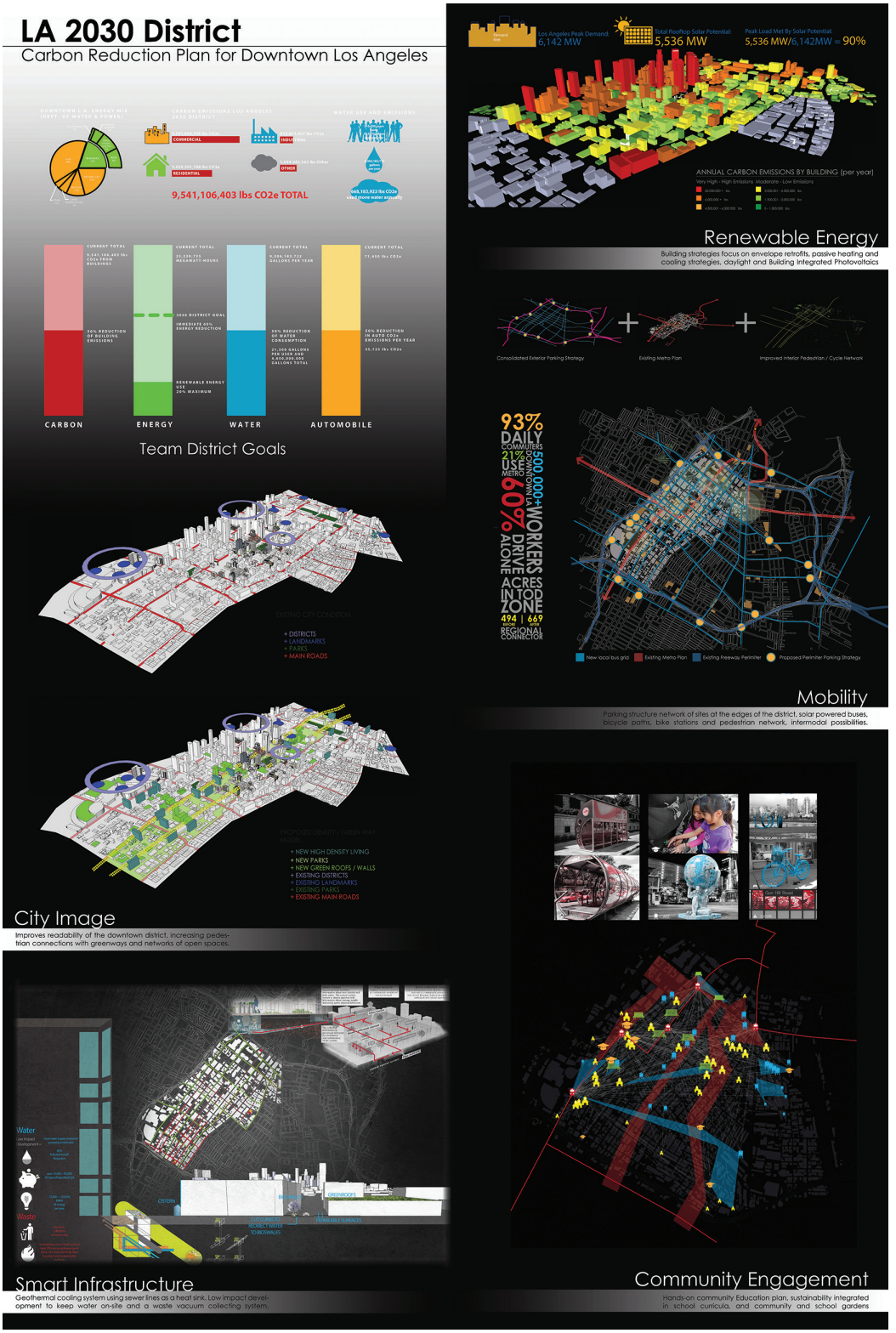


FIGURE 3.27 Carbon reduction plan for Los Angeles 2030 district. (Courtesy of Cal Poly Pomona students.)

FIGURE 3.28 Carbon reduction plan for Los Angeles 2030 district. (Courtesy of Cal Poly Pomona students.)

This proposal was done in the beginning of the quarter and provided a meaningful context for the student projects. Students then developed projects inside the district connected to the proposed networks and which are part of the general master plan (Figure 3.28). These projects included library (Figure 3.29) transit oriented developments, bike parking structures (Figure 3.30), single room occupancy (SRO) housing (Figure 3.31), recreational centers, housing (Figure 3.32), residents for the aging, mixed use projects, performing arts centers, centers for arts and education, and a pediatric and family medical center.

Low-energy envelope (*LE*): As in the beginning year studios, some projects were designed to operate only with passive systems, whereas in other projects, mechanical heating was combined with passive heating and cooling strategies. Students used HEED (Milne, 2001) or Sefaira to determine energy use when mechanical systems were implemented and thermal comfort when only passive systems were used. COMFEN, developed by Lawrence Berkeley National Laboratory, was also used for daylight and shoebox energy modeling. COMFEN uses Energy Plus with a simplified user interface to design key variables in fenestration design. Energy Plus dynamically simulates the

FIGURE 3.29 Library proposal for Los Angeles 2030 district. (Courtesy of Cal Poly Pomona fifth-year student Ben Gallardo.)

effects of key fenestration variables on energy consumption, peak energy demand, and thermal and visual comfort (Figure 3.33). The results from the Energy Plus simulations are presented in graphical and tabular format within the simplified user interface for comparative fenestration design cases to help users move toward optimal fenestration design choices for their project. GHG emissions from energy use were determined by multiplying the energy use calculated with HEED by a conversion factor of 0.62 kg CO_2e/kWh for electricity, the average value for the United States. Students also had to develop concept diagrams to explain the energy-efficient features of the building.

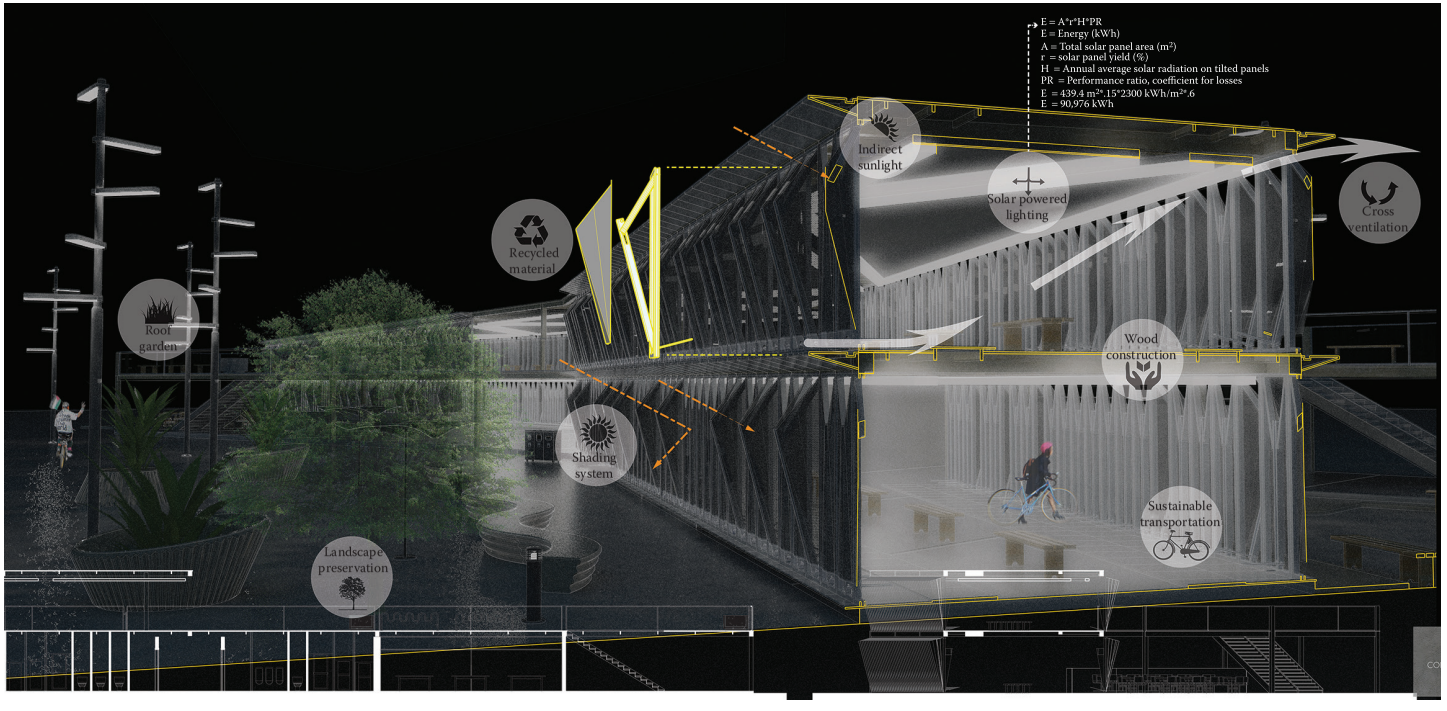


FIGURE 3.30 Bike parking structure for 2030 district. (Courtesy of Cal Poly Pomona fifth-year student Eric Tsang.)

FIGURE 3.31 SRO housing for Los Angeles 2030 district. (Courtesy of Cal Poly Pomona fifth-year student Thomas Concialdi.)

FIGURE 3.32 Housing for Los Angeles 2030 district. (Courtesy of Cal Poly Pomona fifth-year student Hailey Peitzman.)

Figure 3.34 shows sustainable strategies implemented in a student project in Portland. The strategies are organized in four main groups, energy, water, beauty, and health with calculated values for each one. Solar, wind, and water energies generated per year are indicated. Just one apartment unit is shown, but the numbers are for the whole building. The next image (Figure 3.35) shows a student project in the Bronx, New York, where

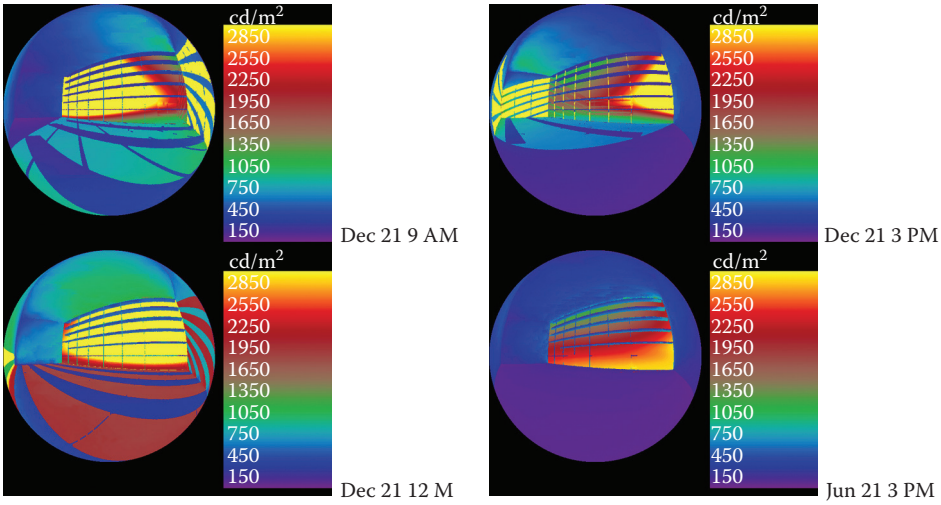


FIGURE 3.33 Daylight analysis for housing in Los Angeles 2030 district. (Courtesy of Cal Poly Pomona student Hailey Peitzman.)

the dominant feature is the green roof. A shadow study was done to determine the best terracing options for the green roofs and to maximize sunlight in the interior courtyard in the winter. Figures 3.36 and 3.37 use diagrams to explain several envelope control strategies. In the first case, a residential building in downtown Los Angeles, the image integrates daylight and glare studies with an understanding of wind direction and shade systems. In the second case for Orange County, additional information is provided for the systems. Figures 3.38 is an example of student envelope strategies in Los Angeles, showing information regarding assembly, construction, and insulation.

Radiation impact on surfaces (*RS*): Building surfaces receive varying amounts of solar radiation depending on the climate and latitude of the site and the orientation and tilt of the surface. Incident solar radiation can have a significant impact on buildings by affecting the surface temperature of opaque materials and thus increasing the rate of heat transfer by conduction, or by radiation and conduction in the case of windows. Surfaces that receive more solar radiation might require additional shading during the summer or would be suitable for solar hot water collectors or photovoltaic panels or to place a window to provide solar gains to the interior of the building. There are several tools that calculate incident solar radiation. Figure 3.39 shows the solar access command in Ecotect was used to calculate and analyze irradiation on the exterior surfaces of buildings in a hot and dry climate. In this type of analysis, also available in other software such as DIVA or IESve, a three-dimensional (3D) model shows incident solar radiation on external surfaces for selected hours and months. This analysis is typically done separately for the cooling and heating seasons. During the heating season higher solar radiation values will usually provide more potential for solar gain and free heating from the sun, while in the summer solar gains should be blocked to avoid overheating. This analysis is not a substitute for developing an energy model, but when used correctly it provides a quick first indication of the effect of solar radiation on exterior surfaces, which helps to design better solar responsive envelopes.

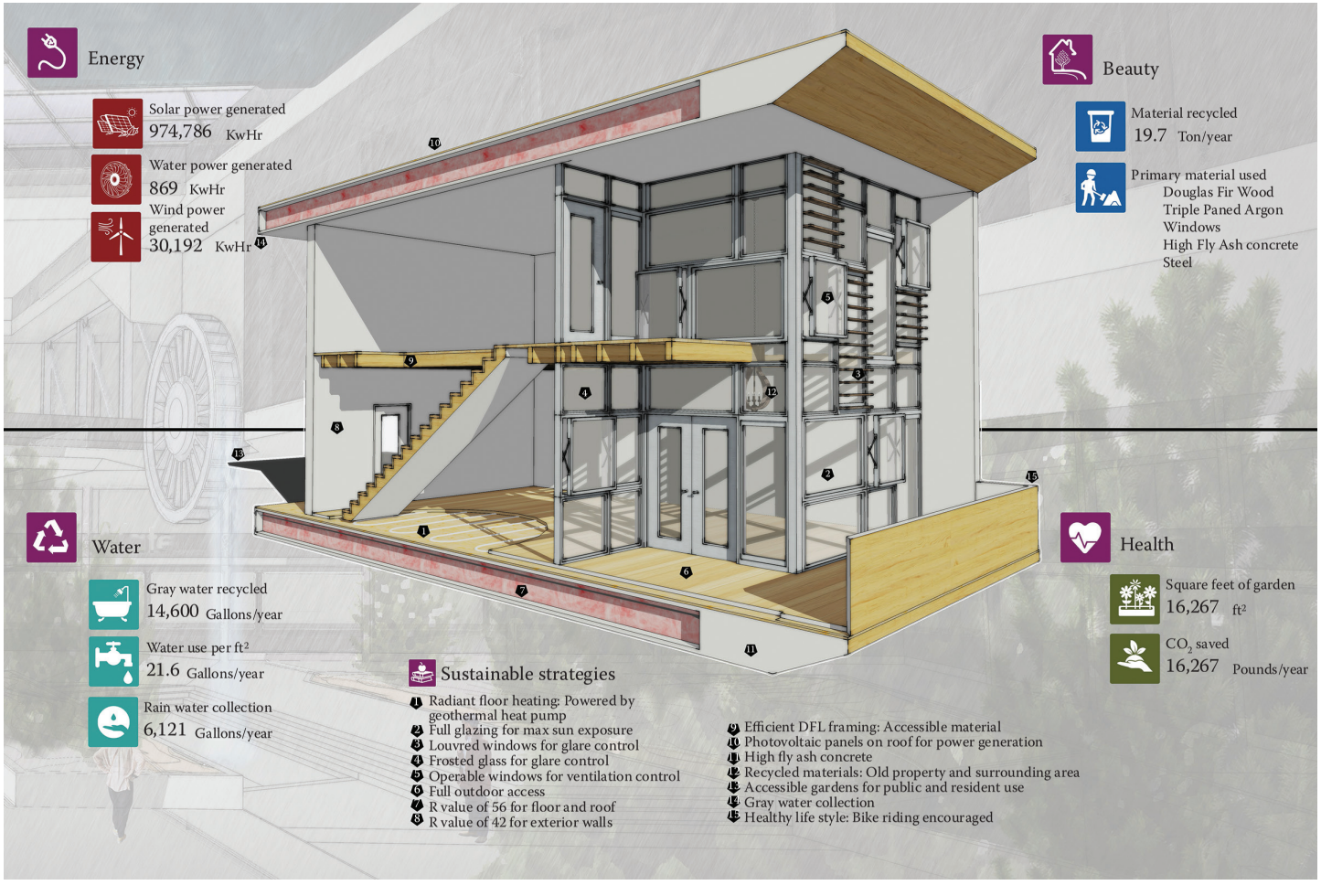


FIGURE 3.34 Sustainable strategies. (Courtesy of Cal Poly Pomona students Hayden Moore and Ben Tunigold.)

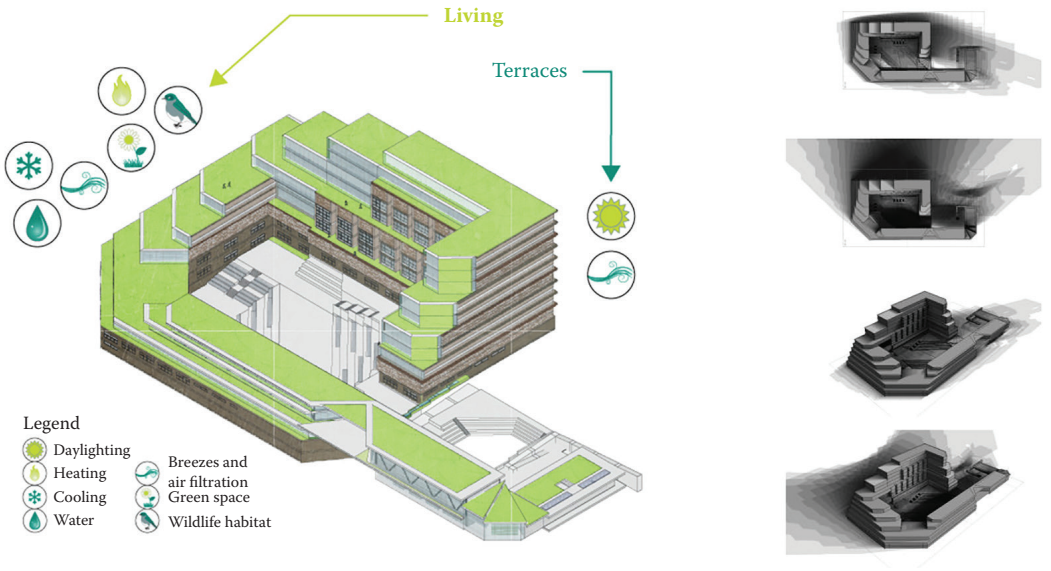


FIGURE 3.35 Sustainable strategies. (Courtesy of Cal Poly Pomona students Megan Turner and Lina Chan.)

Fenestration and shading (*FS*): Solar radiation entering through windows can contribute a significant amount of heat into the building, which can be beneficial when heating is required but can also be a liability when thermal gains must be blocked and cooling is needed. Daylighting, however, should usually be provided during the whole year. Windows and their shading systems should typically block solar radiation in the summer and allow it in the winter (if necessary) while providing daylight. The first step in this process is to determine when solar radiation is needed inside the building. There are several ways to do this; a simple one is to analyze weather files using climate analysis tools. For example, the psychrometric chart from Climate Consultant can be used to determine solar requirements as a function of outdoor temperatures. Climate Consultant also has a sun path diagram that includes temperature and solar position in one diagram, and indicates when shade is needed, using as a reference the outdoor temperature. When available, Ecotect included solar radiation data in the sun path diagram providing guidance to determine critical hours and orientations. The chapter on solar geometry will provide more guidance on the design shading systems based on outdoor temperature, solar gains, cooling or heating loads, or degree days. Solar studies that show the effect of solar radiation on a building envelope can be used to help design shading systems that let winter sun inside while blocking solar radiation in the summer. Figure 3.40 shows a student example of a façade study (upper left of the figure) before and after proposing a shading system, which has been tested for the summer and winter. Vertical shadow angles are calculated based on the sun path diagram with the shadow mask, and percentages of cool, hot, and comfortable hours for the year are shown. Figure 3.41 shows another student solar analysis of a south façade in New York City during the summer and the winter, with more shade in the summer. Students also used the solar access analysis tool with the sun path diagram to determine the incident solar radiation, while a grid inside the space shows irradiation values. Solar radiation can also be studied directly in the interior on a vertical or horizontal surface. The sun path diagram can also be used to determine shading provided

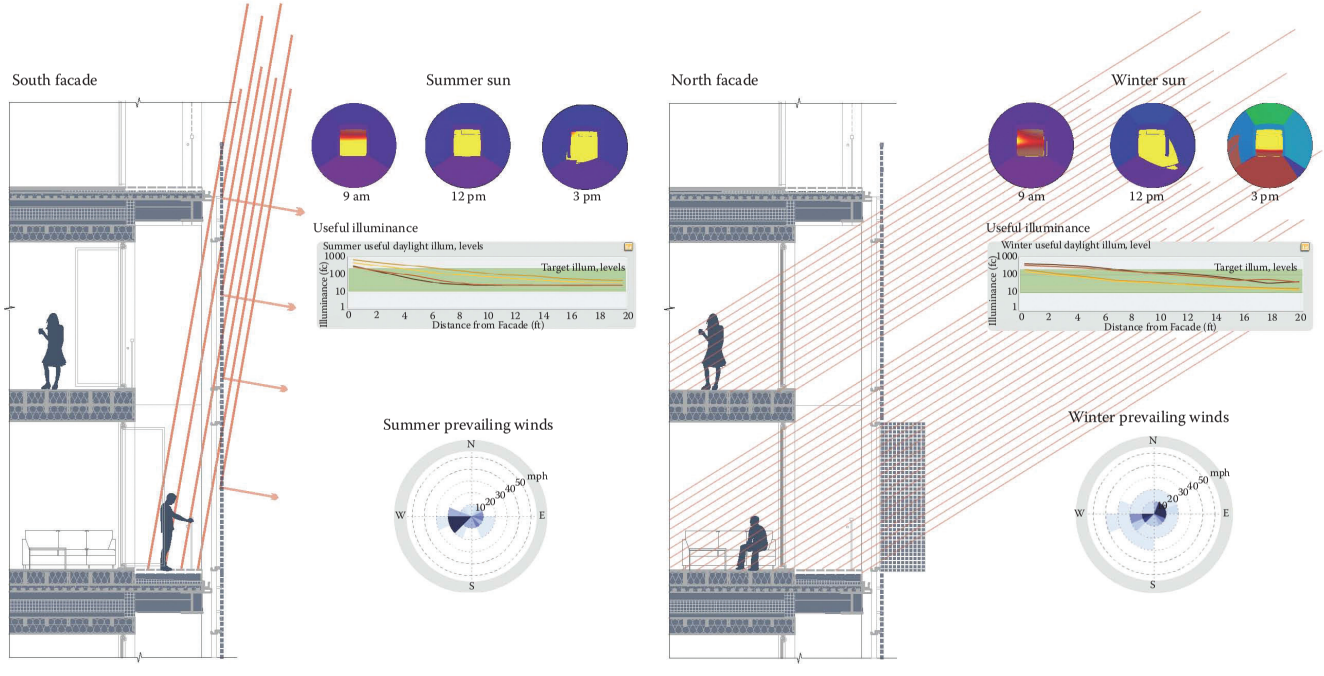


FIGURE 3.36 Shading and envelope controls strategies. (Courtesy of Cal Poly Pomona student Hailey Peitzman.)

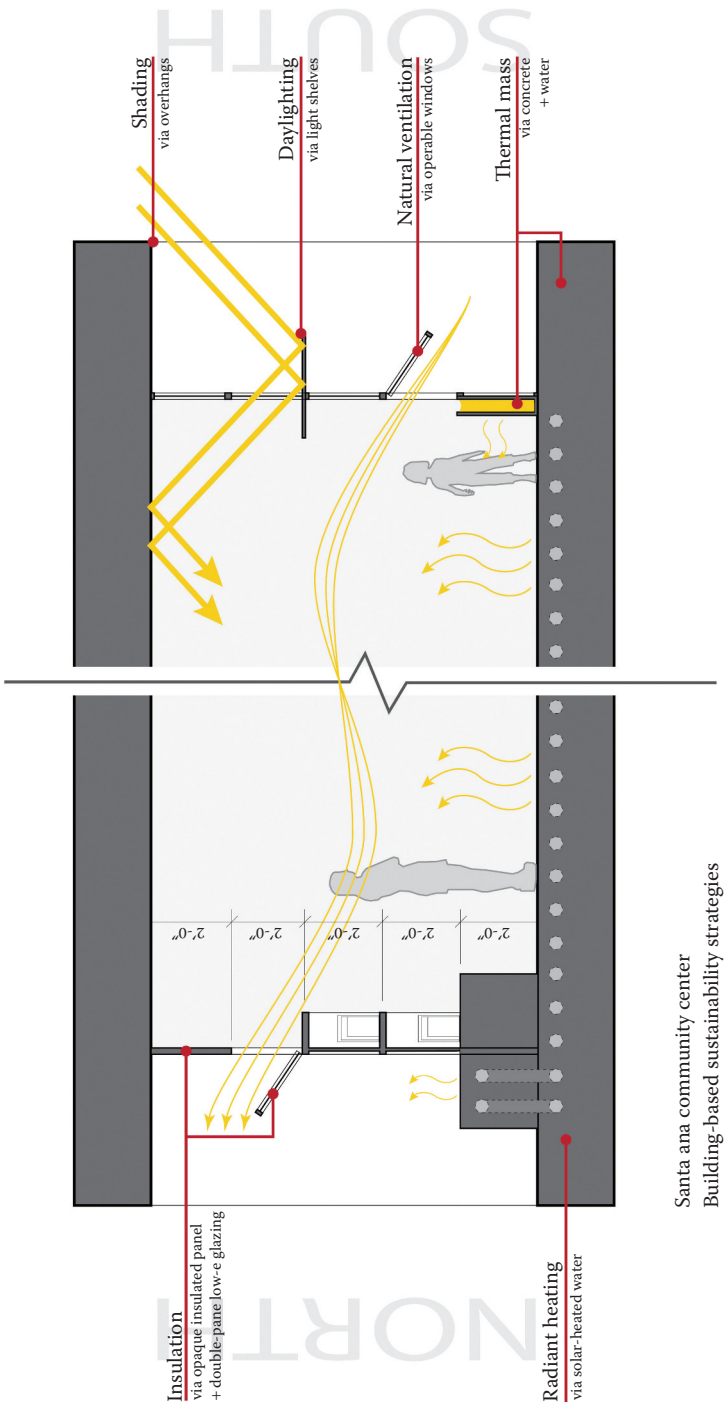


FIGURE 3.37 Envelope controls strategies. (Courtesy of Cal Poly Pomona students Hannah Lee and Ioanna Magiati.)

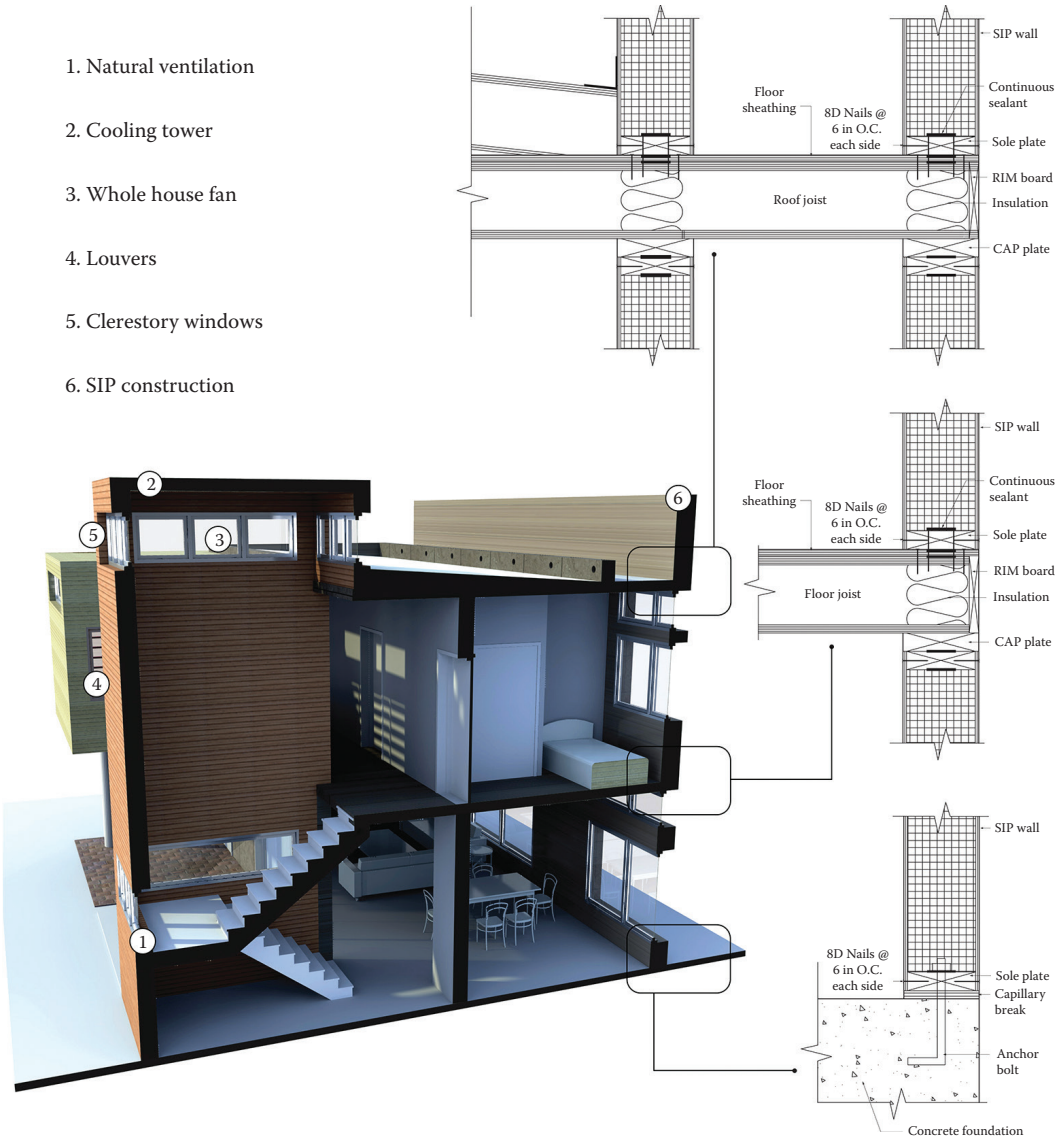


FIGURE 3.38 Envelope strategies. (Courtesy of Cal Poly Pomona student David Castro.)

by exterior elements on windows or when radiation will penetrate into a space through the different openings (Figure 3.42).

Efficient design with daylight (*ED*): It is important to achieve a controlled distribution of light inside a space. Adequate illuminance levels should be provided while eliminating glare. Daylighting can be provided by sidelighting and toplighting. Sidelighting admits light from the perimeter walls of a building and is more effective when the ceiling is above 8 ft high. Toplighting admits light at the top of a building through vertical or horizontal glazing such as roof monitors, clerestories, sawtooth elements, skylights, and atria. Students had to design fenestrations that would achieve required illuminance levels with daylight while minimizing glare. They used different tools, in this case Ecotect and COMFEN to determine if the shading system was providing enough daylight (Figure 3.43). Ecotect's simple analysis assumed cloudy skies

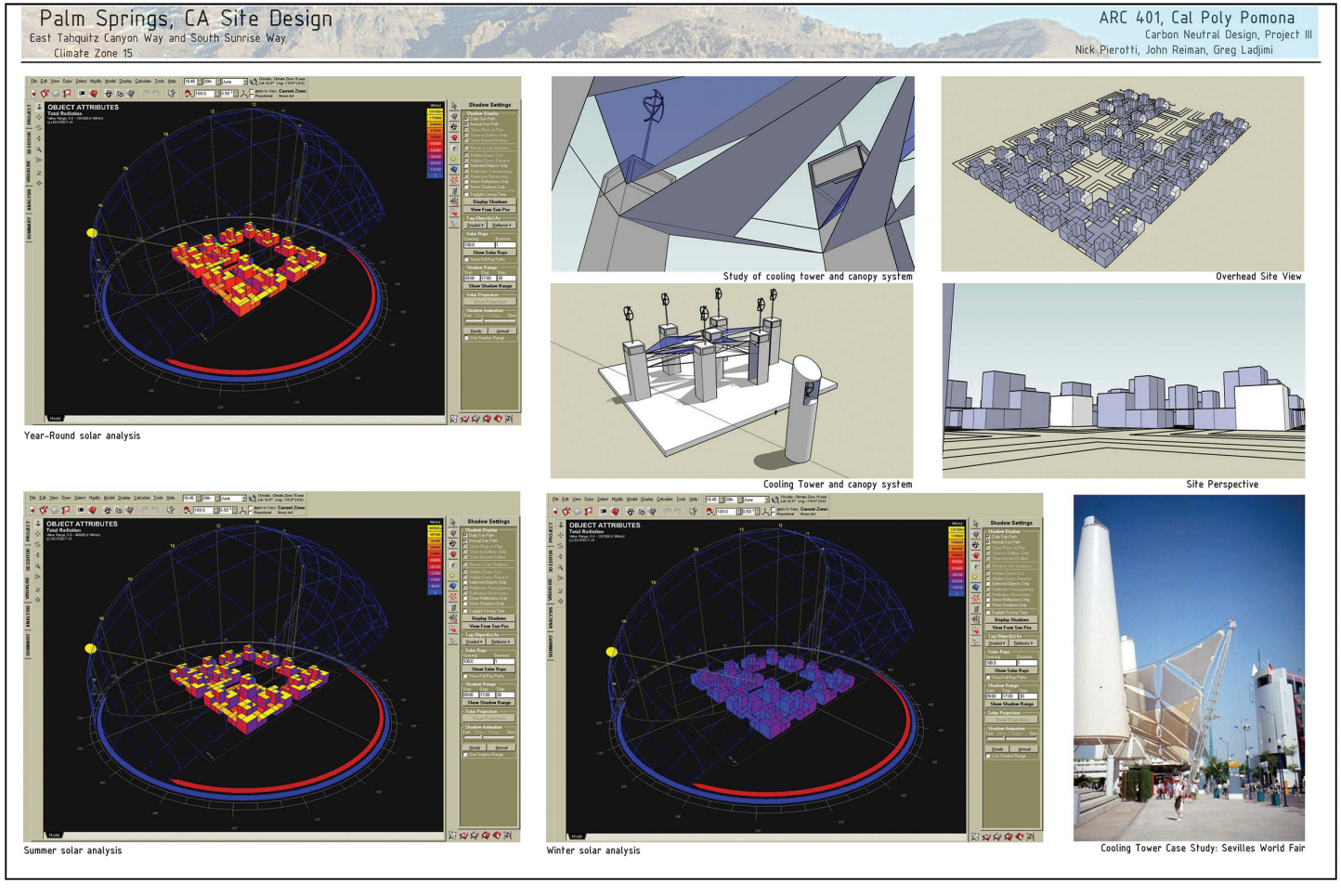


FIGURE 3.39 Solar analysis on surface. (Courtesy of Cal Poly Pomona student Jonathan Reiman.)

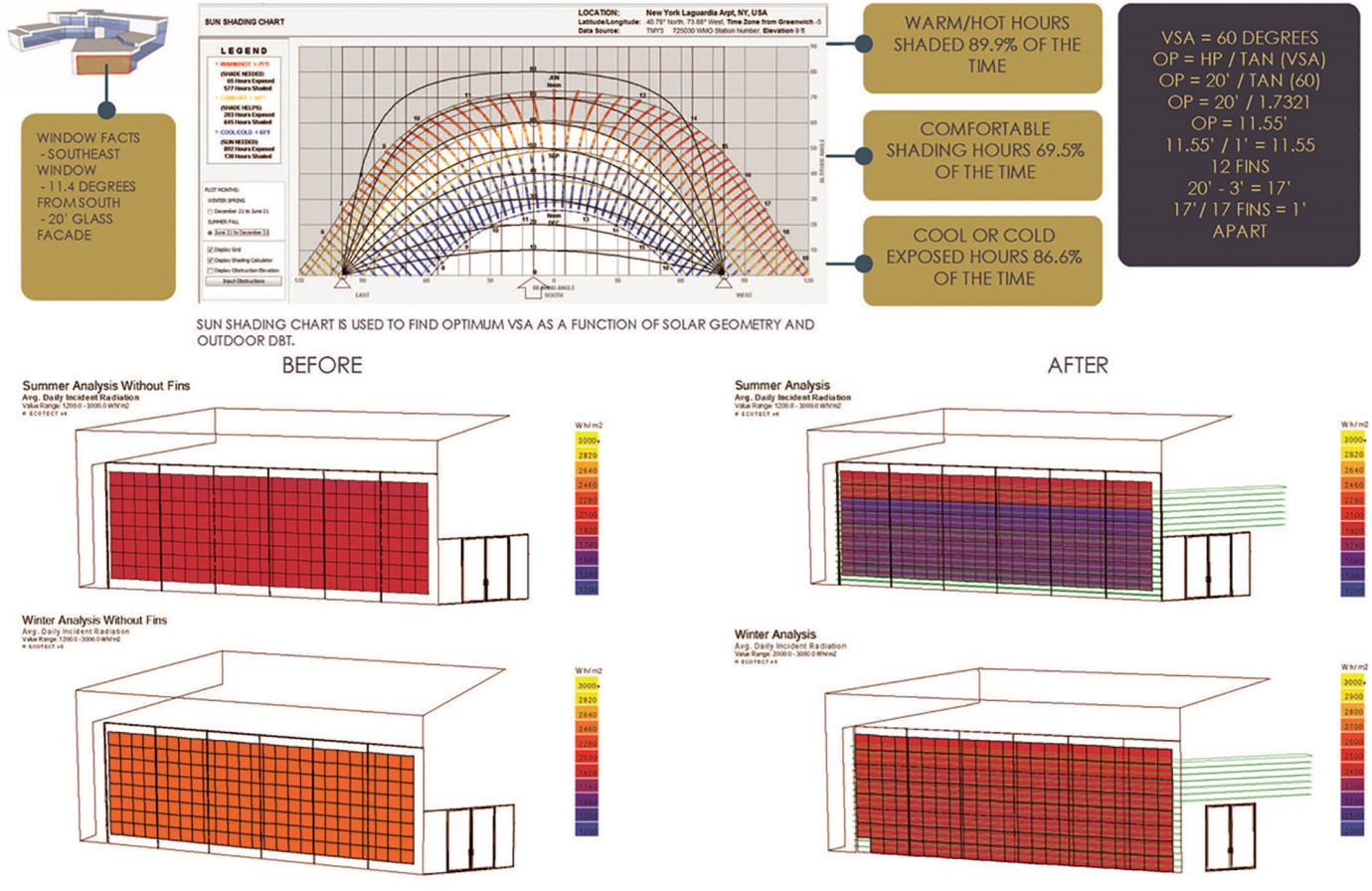


FIGURE 3.40 Solar analysis on surface to adjust shading. (Courtesy of Cal Poly Pomona student Ben Gallardo.)

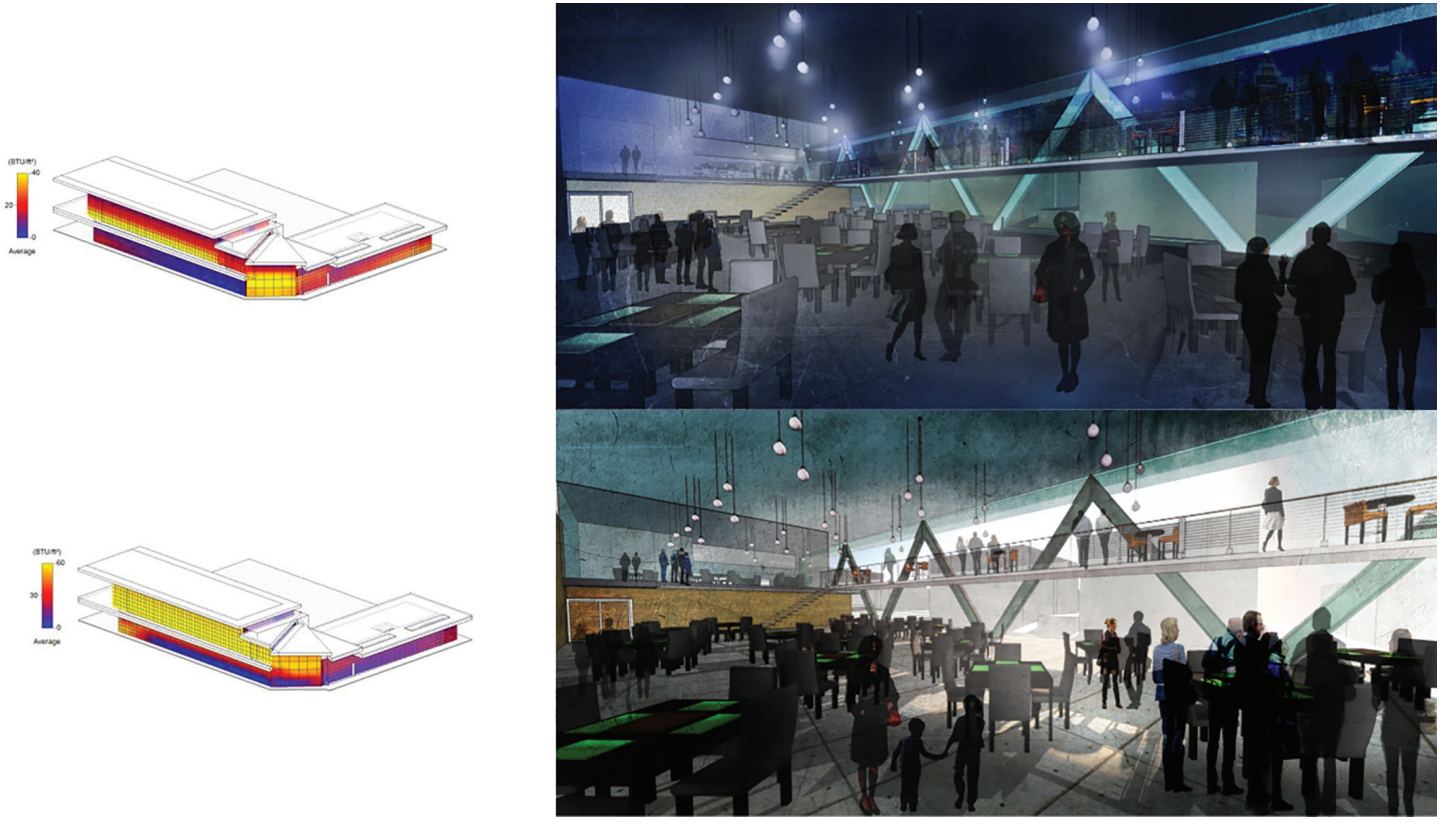


FIGURE 3.41 Solar analysis on surface to compare winter and summer performance. (Courtesy of Cal Poly Pomona students Megan Turner and Lina Chan.)

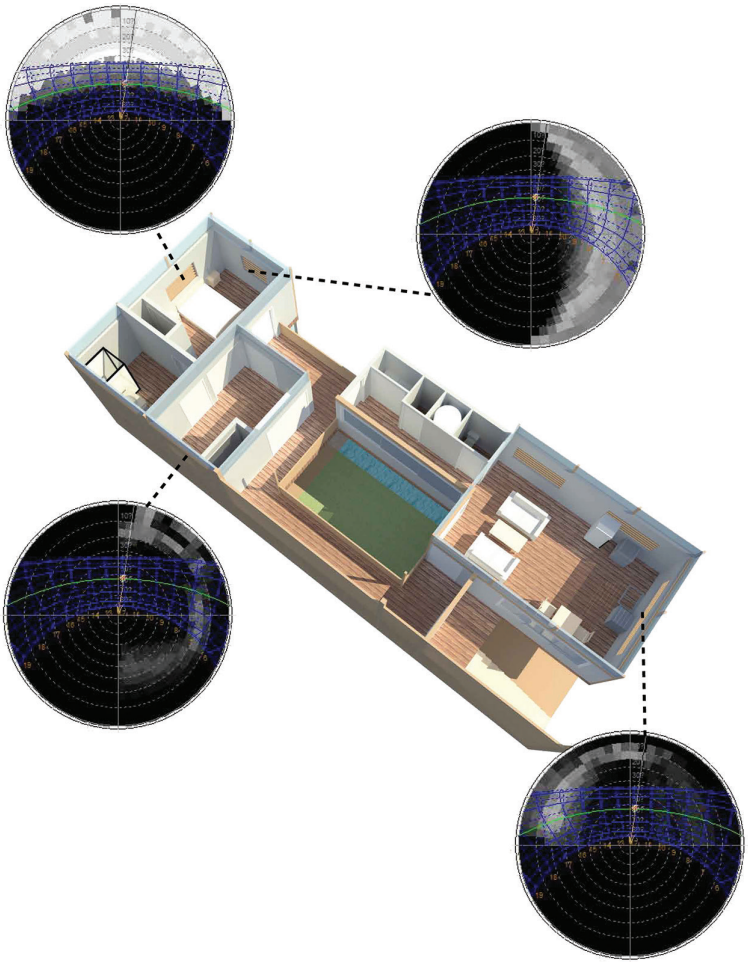


FIGURE 3.42 Solar analysis on windows with sun path diagram. (Courtesy of Cal Poly Pomona student Nancy Park.)

ensuring enough daylight under those conditions, but in clear skies there is potential for glare and overheating. Students also used Ecotect with Radiance, Sefaira, or Diva to calculate illuminance and luminance values (Figures 3.44 and 3.45). COMFEN provides reasonable precision in single spaces using energy plus, while Sefaira has an easy-to-use interface that works with Sketchup and Diva is very easy to use with Rhinoceros. These programs use weather files instead of cloudy skies generating better location specific results. Ultimately the goal of these is to inform the design (Figure 3.46).

Light shelves (*LS*): Light shelves bounce visible light up to the ceiling, which then reflects it down deeper into the interior of a room. A reflective surface will reflect the light with an angle equal to the angle of incidence of the incoming daylight. If the light shelf is painted with a rougher material, then it will provide a more diffuse spread of light, which will scatter the light with varied angles and will provide a more even coverage of the ceiling. If it is finished with a smooth surface, then it could bounce deeper inside the space. The ceiling should be painted with a light color to better reflect the light down into the area underneath. Light shelves reduce glare close to the window and provide a more even distribution of light in the space.

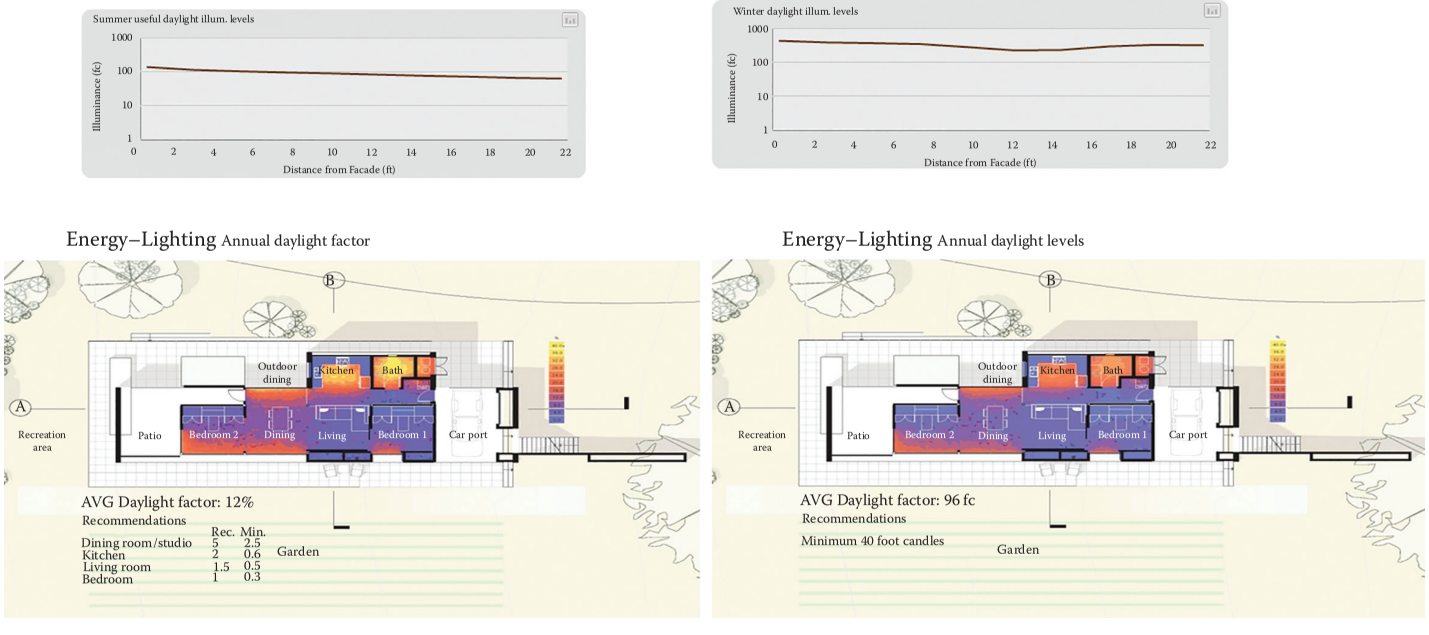


FIGURE 3.43 Simple daylight analysis with Ecotect. (Courtesy of Cal Poly Pomona students Brandon Ro and Aaron Locke.)

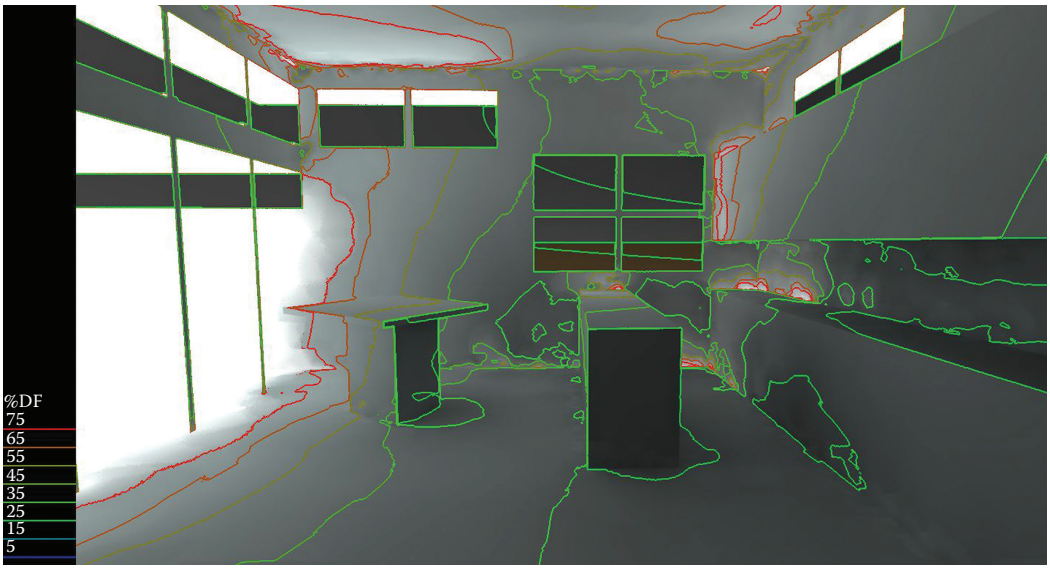


FIGURE 3.44 Daylight analysis with Ecotect and Radiance. (Courtesy of Cal Poly Pomona student Charles Campanella.)

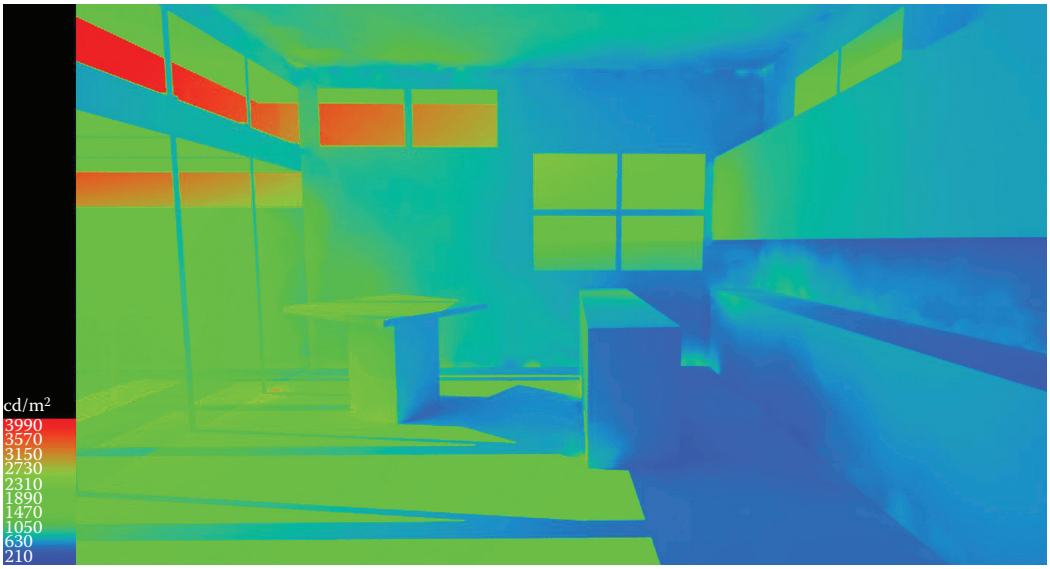


FIGURE 3.45 Luminance analysis with Ecotect and Radiance. (Courtesy of Cal Poly Pomona student Charles Campanella.)

Design with wind (*DW*): Natural ventilation can be a very effective cooling strategy. In hot and humid climates it can provide cooling to our bodies, while in hot and dry climates it can cool the interior structure of the building during the night, which then acts as a heat sink during the day. To adequately implement natural ventilation, it is necessary to estimate how the air flows through the openings and spaces of the building. Using Ecotect and WinAir, students determined the pressures and direction of air movement through different areas of the building. Layers had to be cut horizontally and vertically to understand airflow patterns. Students also used "class-made" wind tunnels in the second-year studio and in the

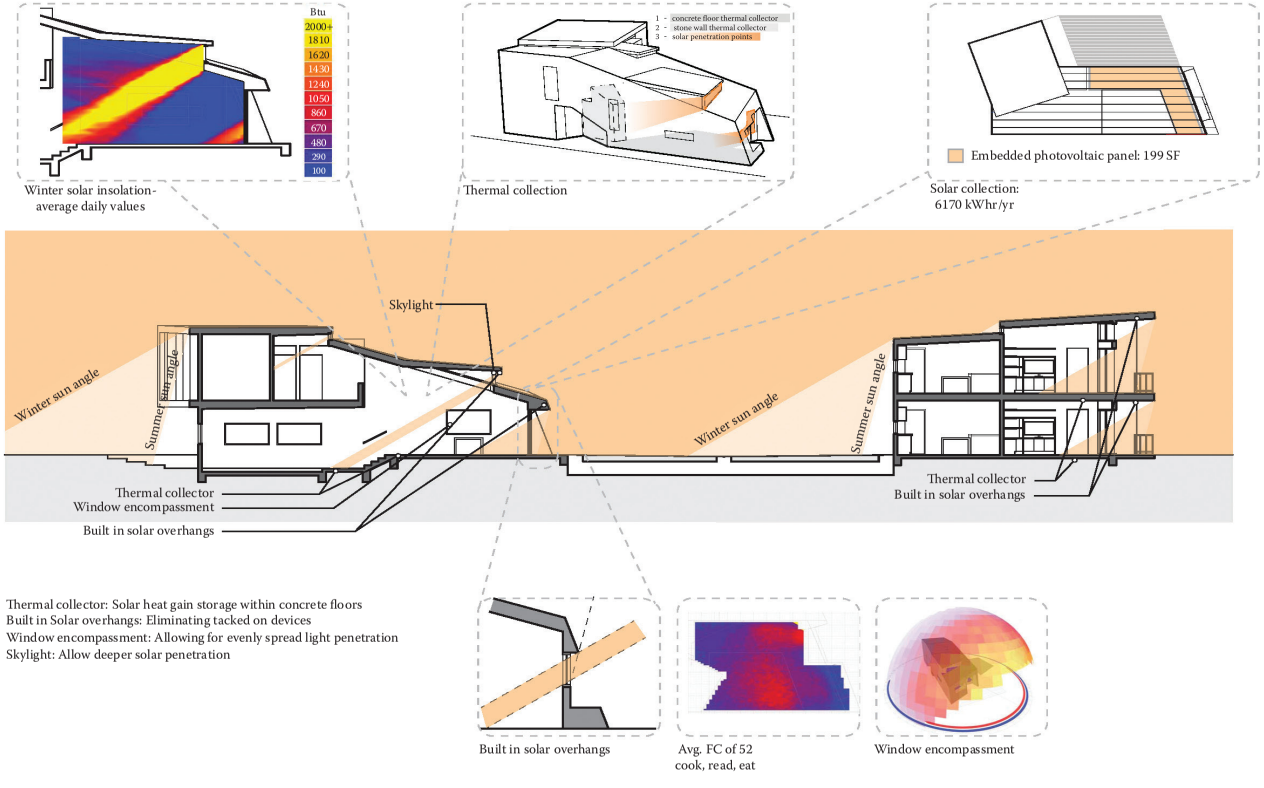


FIGURE 3.46 Daylight and solar analysis guidelines informing design. (Courtesy of Cal Poly Pomona students Calvin Huang and Mathew Trujillo.)

GreenKit project. Even though these are very simple analysis that do not consider thermal buoyancy effects, they permit students to go beyond the "magic arrow" type analysis, and they serve to validate the airflow concepts sketched out by them (Figures 3.47 and 3.48). Figure 3.49 integrates daylighting and wind in one diagram.

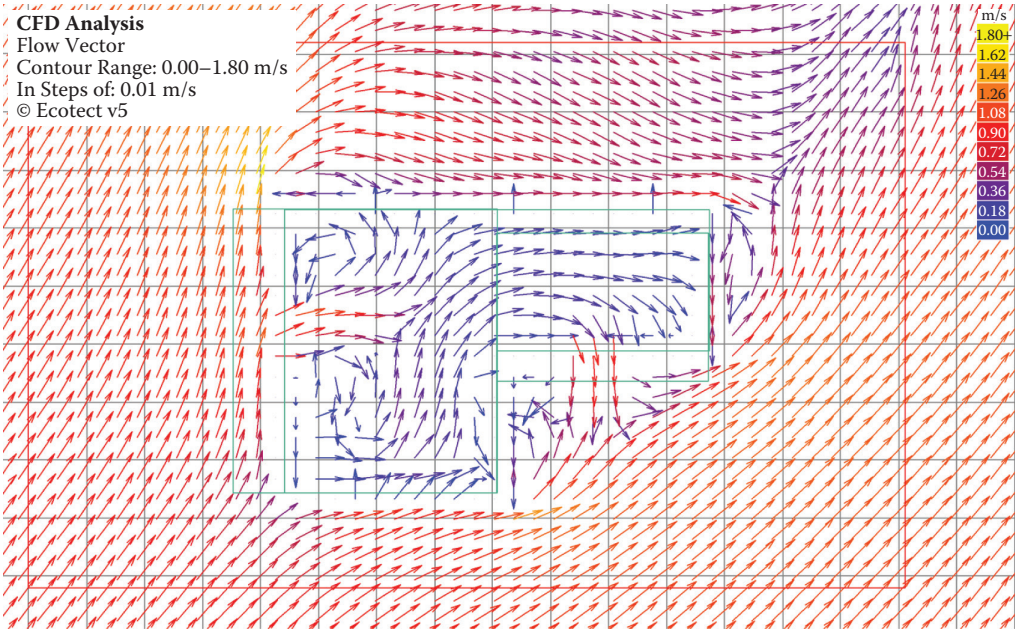


FIGURE 3.47 Airflow analysis with Ecotect and WinAir for the Tijuana house (flow vectors).

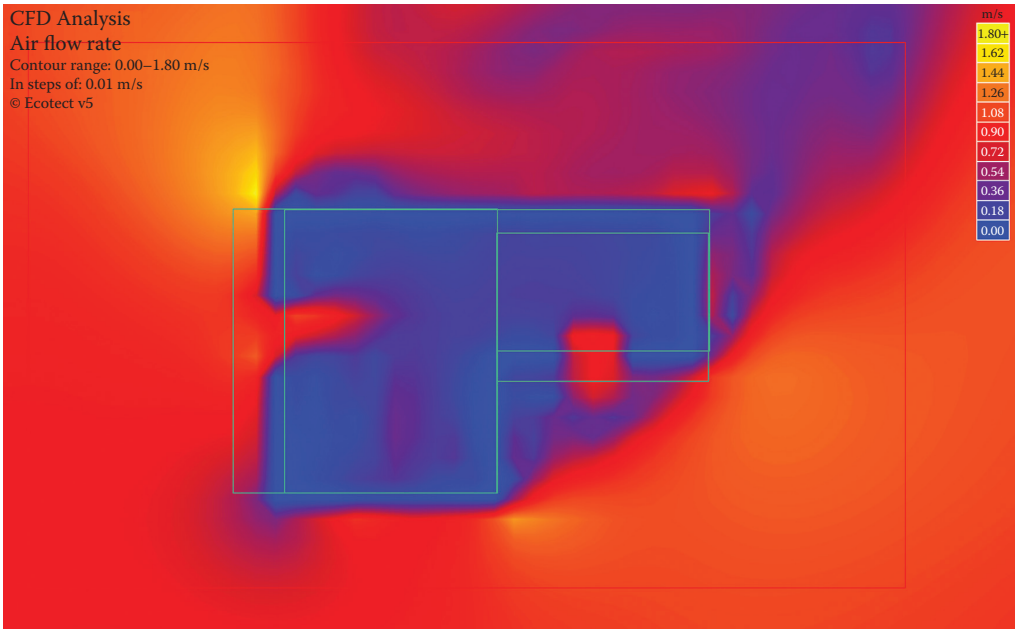


FIGURE 3.48 Airflow analysis with Ecotect and WinAir for the Tijuana house (contour range).

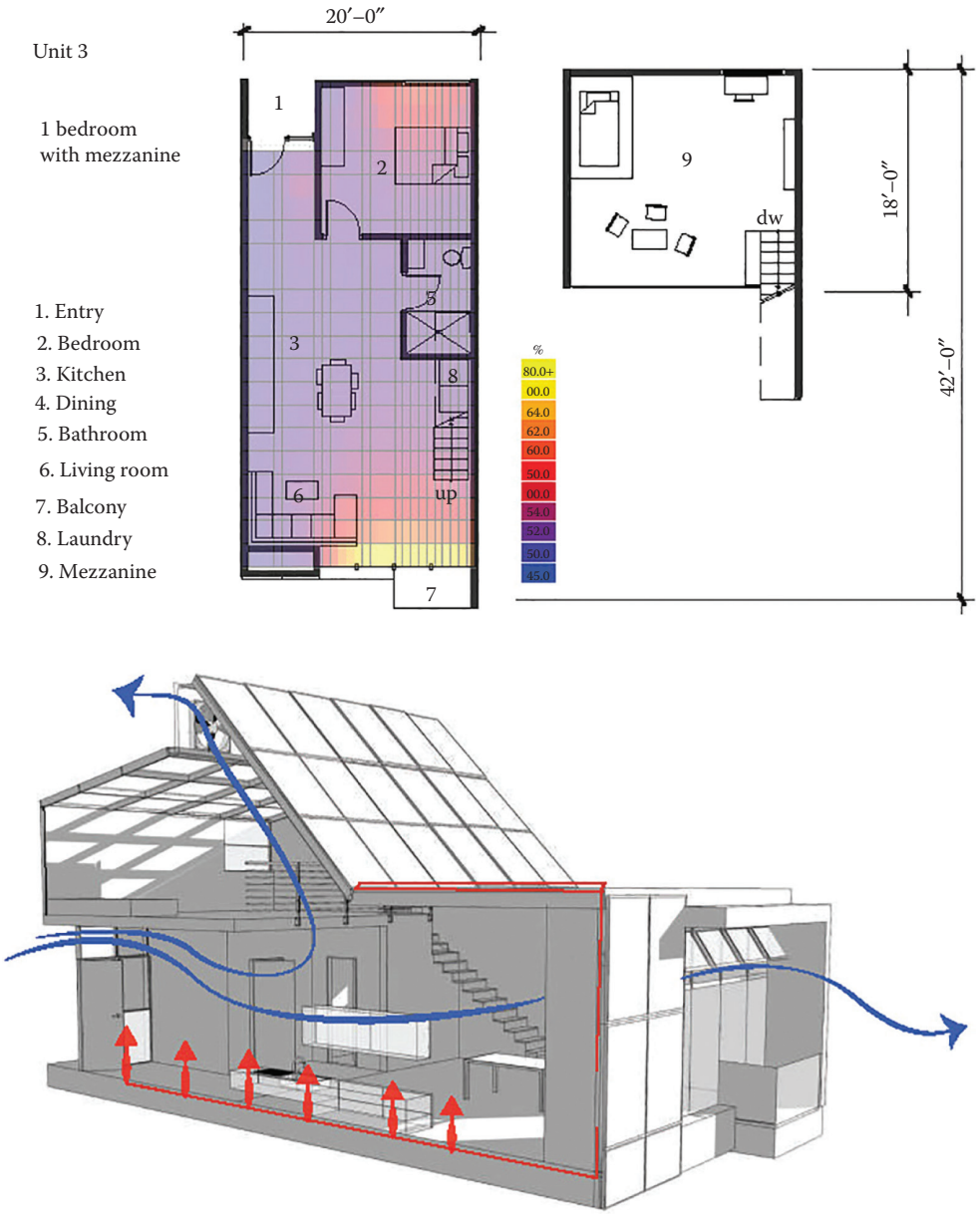


FIGURE 3.49 Conceptual wind and daylight in one diagram.

Direct gain (*DG*): The simplest passive solar heating system is a direct gain system. It consists of an insulated space with equatorial-facing glazing for solar gains that are absorbed by thermal storage mass and reemitted later. Thus, the living space where the mass has been stored is a "live-in" collector. These systems require equatorial-facing glazing with the living space directly behind and an exposed thermal mass in the floor, ceiling, or walls, sized with enough capacity for thermal storage and positioned for solar exposure. Figure 3.50 shows a student proposal for Pamo Valley in which direct gain is used to heat the space.

Solar hot water (*SW*): These are usually mechanical devices whose sole purpose is to collect solar energy in the form of heat and then store it for later use using water as

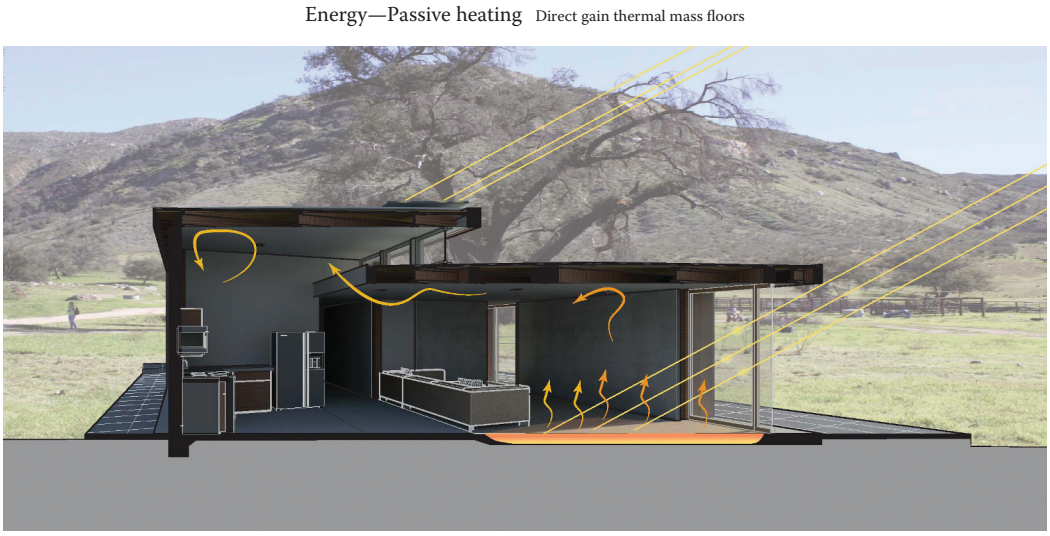


FIGURE 3.50 Passive heating in Pamo Valley House. (Courtesy of Cal Poly Pomona students Brandon Ro and Aaron Locke.)

the working fluid. A solar thermal system usually has three components: collector, storage, and distribution. In the solar collector, the sun's energy is converted to heat in the liquid inside the solar collector's channels. There are two types of domestic solar water heating systems: active, which have circulating pumps and controls, and passive, which do not. There are three main types of collectors, flat-plate collectors (glazed and unglazed), integral collector-storage systems, and evacuated-tube solar collectors. Glazed flat-plate collectors are insulated, weatherproofed boxes that contain a dark absorber plate under glass or plastic covers. Several students tested very cheap easy-to-build flat-plate solar collectors.

The main applications of solar thermal heating are domestic water heating (DWH), space heating, and direct solar pool heating. Domestic water heating is an area of high potential for the application of solar energy in homes. There are many types of systems and they differ in how the transfer fluid is circulated between collector and storage tank and the freeze protection provided. In space heating systems, solar energy collected at relatively low temperatures can be used for space heating through radiant floors. Space heating needs more energy and the needs are seasonal. Some students tested solar hot water systems for space heating through radiant systems and some tested for domestic solar hot water. Domestic systems were based on the thermosiphon effects without any pumps. Cal Poly Pomona students built a very-low-cost solar hot water system using a discarded heat exchanger from a refrigerator and low-cost components (Figure 3.51). This system is proposed for space heating by radiation and not for domestic solar hot water and was developed to provide heating in uninsulated buildings in northern Baja California, Mexico. The goal was to use discarded refrigerators as a potential source of free material for the system. Several low-cost and recycled materials were used: an insulated frame from the refrigerator door, a discarded glass pane, the fridge evaporator coil, the existing filaments on coil, the rear metal panel of the fridge, the discarded drink tank, and drinking water pipes and valves.

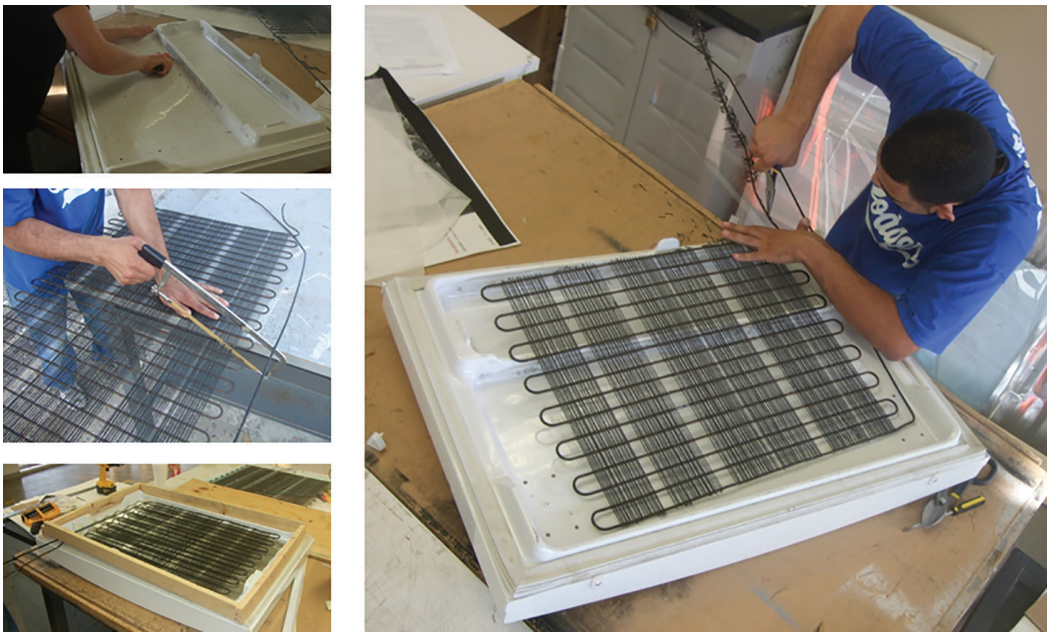


FIGURE 3.51 Very-low-cost solar hot water system components for less developed countries. (Courtesy of Cal Poly Pomona students Erica Christie, Felipe Ortega, and Mark Erler.)

The solar collector absorbs heat incident on the coils during the daytime, the water circulates through the heated solar collector, transferring the heat to the storage tank and the warmer water is toward the top of the storage tank. In the evening the hot and cold valves are reversed so that the pump draws water through the radiator coil to produce heat inside the house. Students tested the system by placing the solar collector and a radiator inside a test pod. They were able to warm the test cell 9 F above outdoor temperature at night (Figures 3.52 and 3.53).

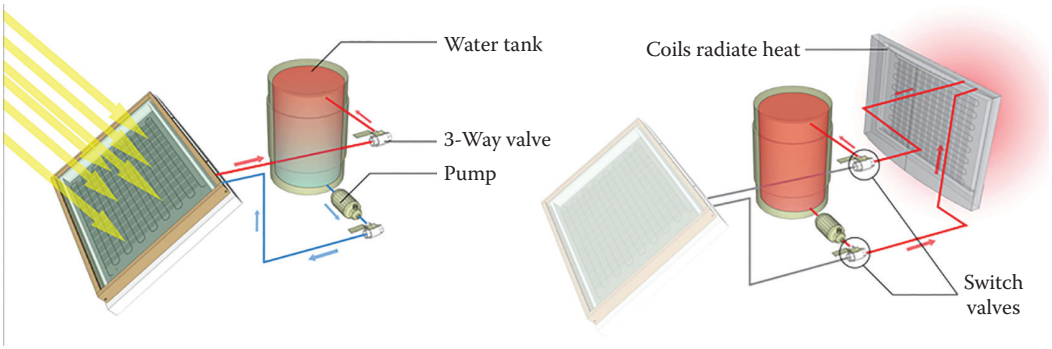


FIGURE 3.52 Very-low-cost solar hot water system performance. (Courtesy of Cal Poly Pomona students Erica Christie, Felipe Ortega, and Mark Erler.)

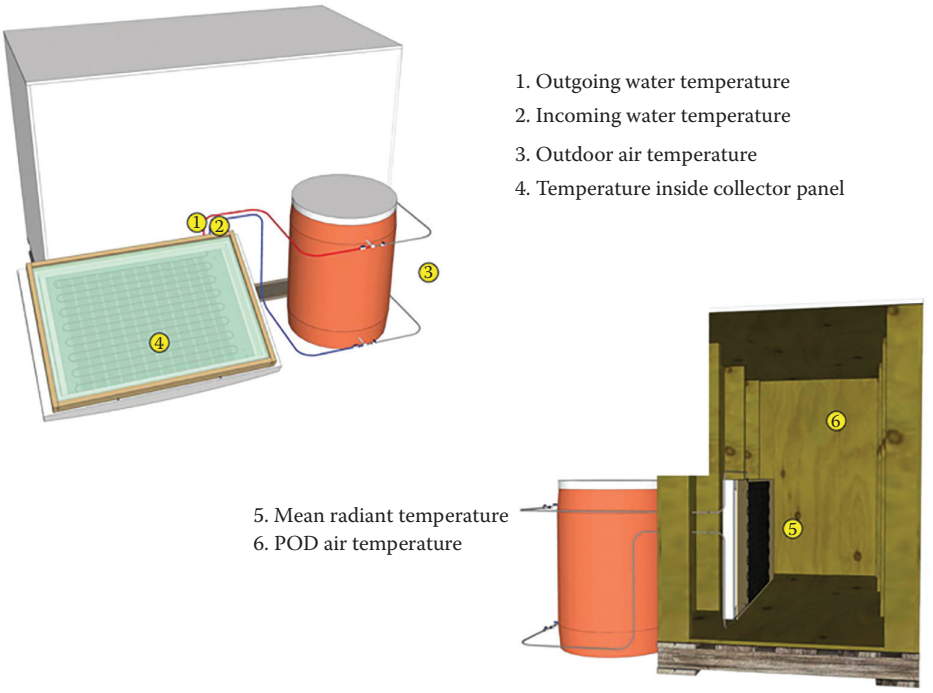


FIGURE 3.53 Very-low-cost solar hot water system testing. (Courtesy of Cal Poly Pomona students Erica Christie, Felipe Ortega, and Mark Erler.)

Photovoltaic systems (*PV*): A PV array produces power when exposed to sunlight and has a number of other components to conduct, control, convert, distribute, and store the energy. Usually students calculated the total building load with an energy modeling program such as HEED or Sefaira, or estimated with a spreadsheet. They then used tools such as PVWatts to calculate and design the photovoltaic system, the most common type of renewable energy system proposed. Figure 3.54 shows a single-family proposal in Pamo Valley while Figure 3.55 shows a larger residential project in Portland Oregon, in which solar panels had to be extended over much of the south facade. Other students explored combinations of several different methods to obtain energy (Figure 3.56).

Modular design (*MD*): Modulation in architecture is important to maximize structural and functional efficiency with minimum use of materials. Modular design is also important when designing a building for deconstruction or adaptation to another function and provides a building with more flexibility (Figures 3.57 and 3.58).

Low-carbon materials (*LC*): GHG emissions from construction occur during the fabrication and transportation of materials to the building and the construction of the building. Between 10%–20% of the total embodied carbon footprint of any construction project and 100% of the total embodied carbon footprint of any landscape project is released the year the project is built or installed. Materials with low embodied energy (and thus little embodied GHG) should be used. Reducing embodied carbon in building materials is a practical mitigation option for buildings by utilizing carbon sink and low-carbon materials and products in buildings.

It is not easy to precisely calculate GHG emissions embodied in materials because after determining the quantities of each material in the building, the origin, manufacturing process, and the

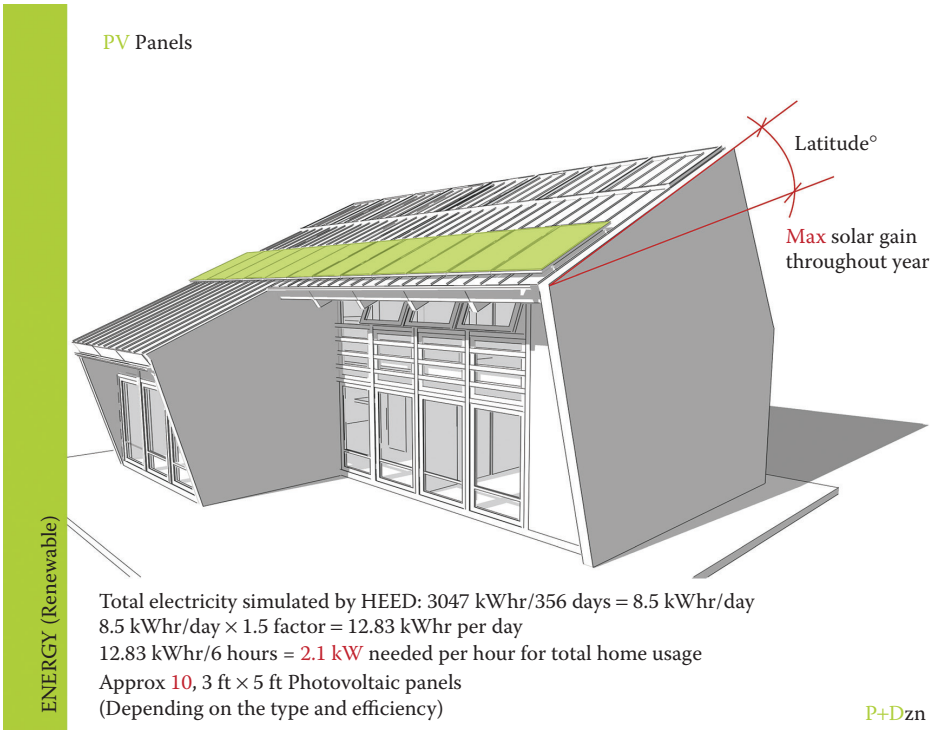


FIGURE 3.54 Solar energy in Pamo Valley Home. (Courtesy of Cal Poly Pomona students Dimitrios Tolios and Parinaz Behbahani.)

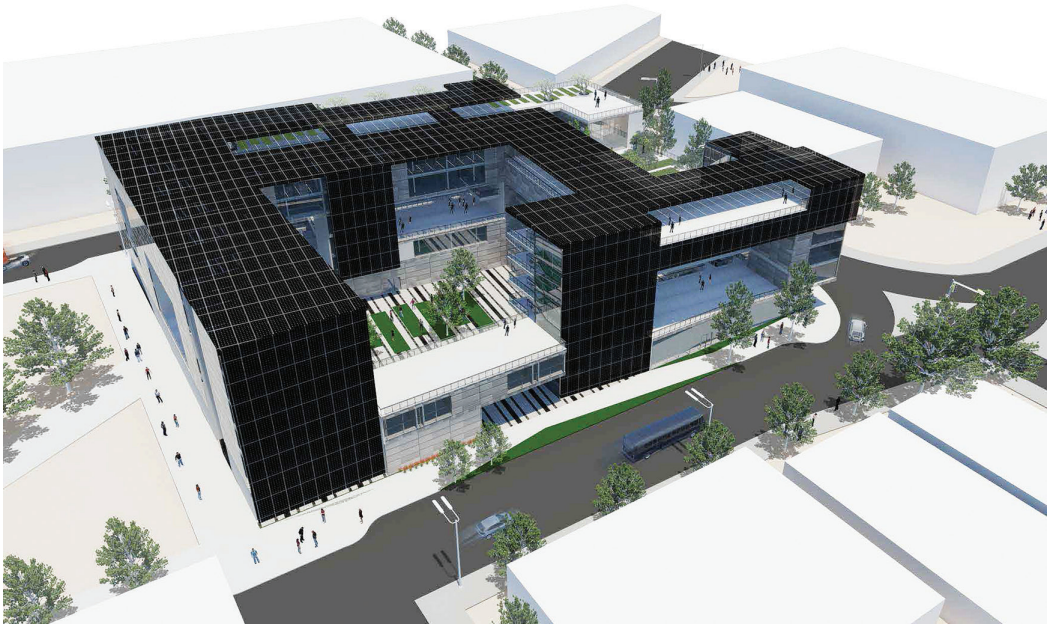


FIGURE 3.55 Solar energy in multifamily housing. (Courtesy of Cal Poly Pomona student Eduardo Gandara.)

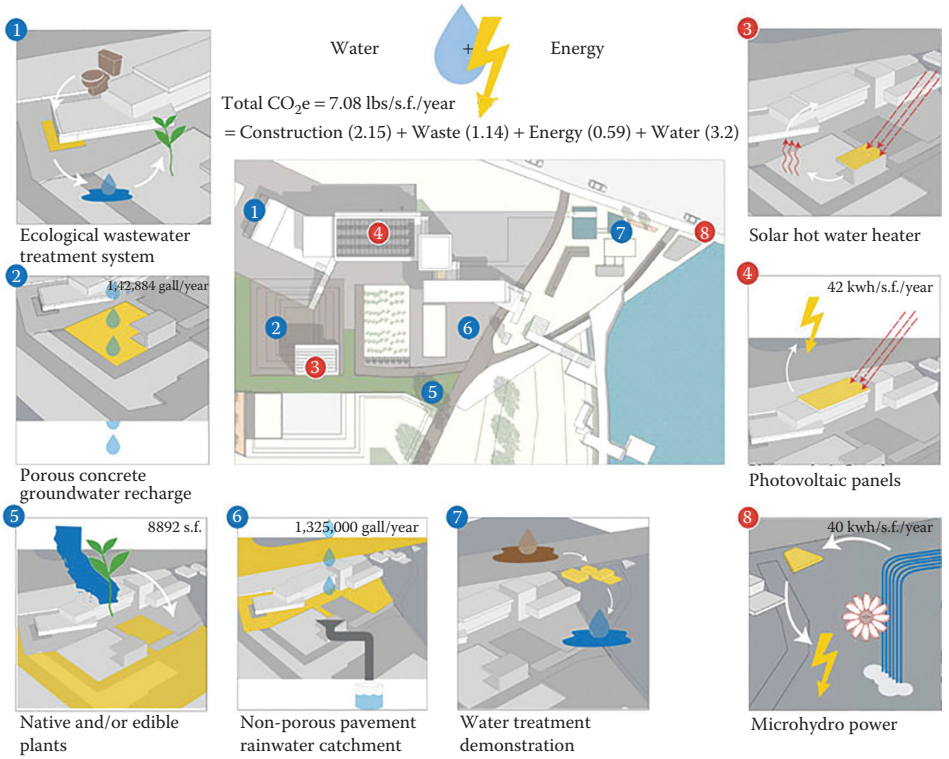


FIGURE 3.56 Sustainable strategies including energy generation. (Courtesy of Cal Poly Pomona students Hannah Lee and Ioanna Magiati.)

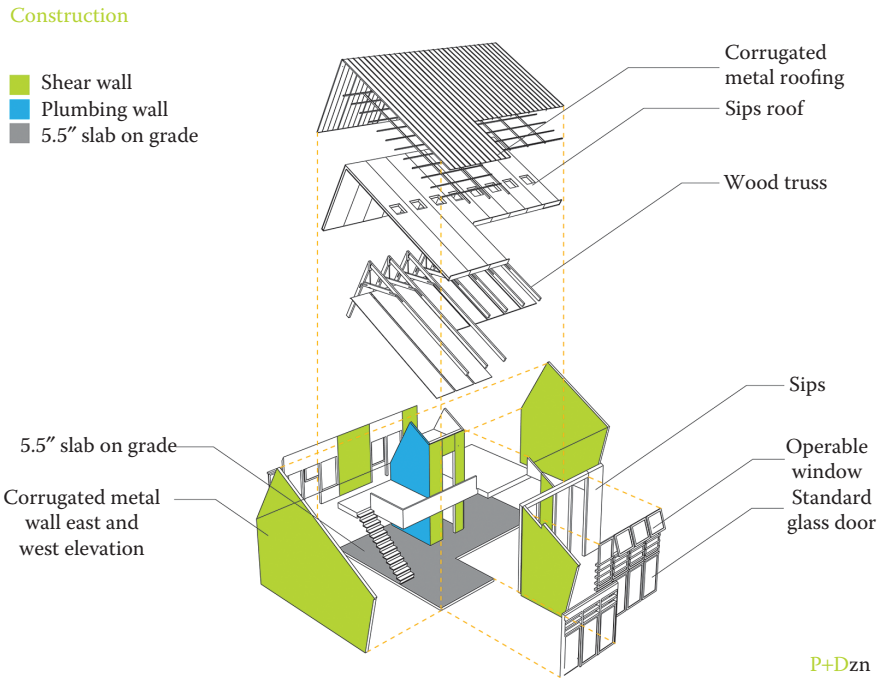


FIGURE 3.57 Mixed construction system. (Courtesy of Cal Poly Pomona students Dimitrios Tolios and Parinaz Behbahani.)

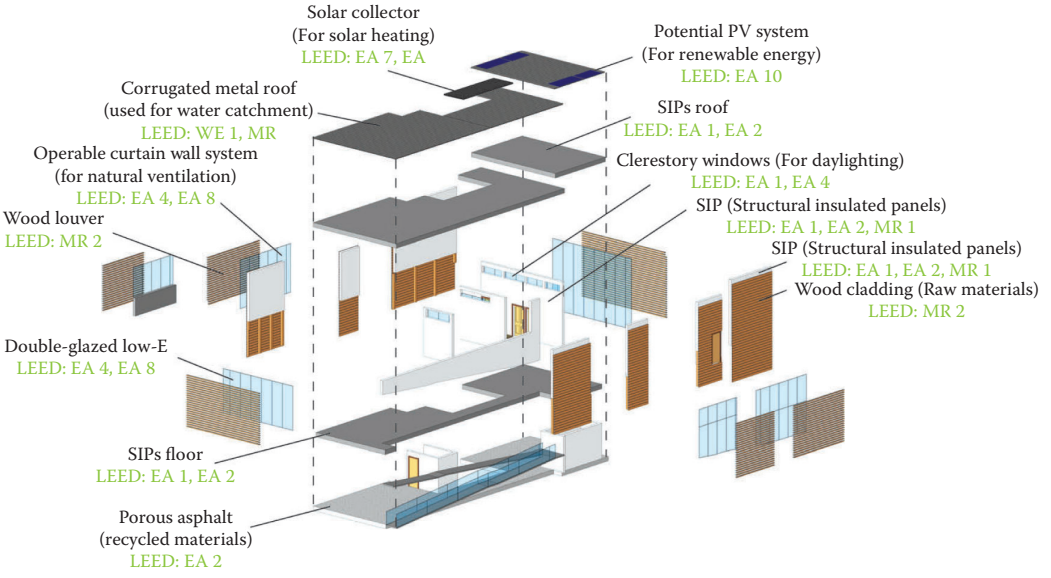


FIGURE 3.58 Material selection and building in integrated sustainable strategies. (Courtesy of Cal Poly Pomona student Leslie Cervantes.)

transportation method and distance from the origin to the site must be calculated for each material. More nonrenewable energy used to fabricate a material means that more carbon will be embodied in it. The distance and method of transportation of the material to the construction site also affects embodied emissions; materials that must be transported a long distance less efficiently will usually have higher values of embodied emissions.

There are several tools to estimate embodied emissions in the building, and some of those used by the students are briefly described. Buildcarbonneutral (http://buildcarbonneutral.org/) provides results based on site disturbance, landscape and ecosystem installation or restoration, building size, and base materials of construction. It can be used early in the design process because the results can be used to address the reduction of that footprint. According to the developers the results are accurate within 25%, plus or minus. The building data take into account site excavation, shell and core (structural systems, building envelope, and building systems). Carbon cost estimates are based primarily on commercial or multifamily projects and the building data assumptions are based on life-cycle balancing assuming the following factors: shell known—12%, shell unknown—12%, service systems—22%, service sector—14%, substructure known—2%, substructure unknown—3%, other/miscellaneous—5%. For the landscape date, developers assumed soil organic carbon (SOC) only and did not include above-ground biomass (trees, shrubs, and grasses). The land use categories are very broad and refer largely to mature natural landscapes: 5 years for grasslands, 10 years for shrub lands, and 30 years for forests, which have more cabon embodied in them.

Athena Institute's Eco Calculator for assemblies (http://www.athenasmi.org/our-software-data/ecocalculator/) is a free software tool that provides LCA results for many common building assemblies. The EcoCalculator is an Excel spreadsheet workbook, with tabs for various categories of structural assemblies (columns, beams, floors, etc.). The student finds specific assemblies for the project and enters the total square footage for each one. Embodied fossil energy use and several impact measures including global warming potential, acidification potential, eutrophication potential, and smog potential are displayed. The EcoCalculator results

consider all life-cycle stages: resource extraction and processing, product manufacturing, on-site construction of assemblies, transportation, maintenance and replacement cycles over an assumed building service life of 60 years, and the demolition and transportation of nonmetal materials to landfill.

BEES (Building for Environmental and Economic Sustainability) software was developed by the NIST (National Institute of Standards and Technology) Engineering Laboratory (http://www.nist.gov/el/economics/BEESSoftware.cfm). It uses several standards and is designed to be practical, flexible, and transparent. BEES Online includes actual environmental and economic performance data for 230 building products (http://ws680.nist.gov/bees/help/Bees%20Online%20Products.pdf).

BEES measures the environmental performance of building products by using the life-cycle assessment approach specified in the ISO 14040 series of standards. All stages in the life of a product are analyzed: raw material acquisition, manufacture, transportation, installation, use, and recycling and waste management. Economic performance is measured using the ASTM standard life-cycle cost method, which covers the costs of initial investment, replacement, operation, maintenance, and disposal. Environmental and economic performances are combined into an overall performance measure using the ASTM Standard for Multi-Attribute Decision Analysis. Environmental performance weights can be assigned based on the EPA or BEES, or user defined. These weights are then used to evaluate the product also based on economic performance, and again different weights can also be assigned to determine performance of materials.

Another tool under development by Portland State University calculates the embodied energy and carbon in structural systems (http://www.web.pdx.edu/~cgriffin/eecc/). The tool allows exploring the environmental impacts of the recycled content and cement replacement in the materials used for parking structures.

After using these calculators, students divided total embodied emissions by the estimated life of the building to obtain the emissions per year in kg CO_2e/year. Fifty years was the typical number used, the life of the building affecting the impact of embodied carbon. Some of these materials can also be used in different sustainable strategies (Figure 3.58).

Rammed earth construction for a building in the Cerro Azul Community Center in Mexico is an example of a material with a low embodied energy. Durable materials that require less maintenance and last longer are also more effective toward achieving the goal of a carbon-neutral building.

Responsibly harvested wood is a good material to use because it does not require energy to fabricate and is harvested from trees that capture carbon through photosynthesis. Fifty percent of the dry weight of wood is carbon, and the amount of carbon in one cubic meter of wood is similar to that in about 350 L of gasoline (Labbe, 2010). For wood to perform well as a low-carbon building material or even as a carbon sink building material, it should be sourced from harvested wood products. Wood from illegal forest logging is not carbon neutral because it destroys vast natural carbon sinks and their associated biodiversity, which cannot be easily restored. Using nonsustainably harvested wood products is more environmentally detrimental than the benefits provided by using low-carbon materials in buildings. Harvested wood building materials and products can be used in multiple locations in the buildings including flooring and cladding materials, window frames, doors, furniture, structural columns, beams, and rafters. Substituting one cubic meter of aluminum frame for a cubic meter of wood frame reduces emissions by about 85%. Materials such as steel and aluminum have a large amount of embodied carbon but, in many cases, can also be reused or recycled. Thus, metal products are considered to be high-embodied carbon materials because the extraction and refinement processes involved are carbon intensive. However, there are many ways in which the carbon intensity of different

metal products can be reduced, such as recycling or reusing them. Using nonbuilding metal products in buildings can also reduce the carbon footprint of a traditionally carbon-intensive material. Research is continuously under way into multiple types of low-carbon materials, or methods by which to reduce the carbon content of current materials, for example, concrete, that includes fly ash as one of the aggregates or different construction materials that also have different varieties of recycled components.

Wood is very carbon efficient because it absorbs carbon dioxide from the atmosphere to grow. Carbon emissions in wood should account for the carbon released converting the wood from a natural forested state to an installed condition. If these values are reduced, such as in certified wood, wood in a building is a carbon sink. If all the timber at the end of its life in the building were to be burnt in a waste-to-power plant, the use of timber would definitely be carbon negative and could be accounted for as a carbon sink. It is important to minimize waste wood during construction because rotting wood gives off part of its carbon content as methane, which is 21 times more powerful a GHG than carbon dioxide.

Sustainable landscapes: During its operation phase, after a building is constructed, its carbon footprint is the sum of the operational carbon released, mostly from energy, and the landscape carbon sequestered over its life, which could be between 30 and 80 years. Different types of landscapes absorb more carbon than others. Wetlands, for example, store much more carbon than grasslands. In all landscapes, the carbon is released when it is disturbed or destroyed. Landscape can be an important carbon sink that should also be considered when designing with carbon neutrality as a goal.

Zero-waste construction (*ZW*): This refers to optimization of the construction process to reduce construction waste and solid waste. GHGs are also produced by the construction machinery and the transportation of supplies, materials, and people to the construction site. This process is usually out of the scope of the architectural design studios.

Native plants (*NP*): Native plants provide multiple benefits to people and wildlife, while contributing to create healthy soils in urban and rural areas, reducing fertilizer and pesticide use. They also save water because they are accustomed to local conditions, including temperature and rainfall. The deep root systems of many native plants increase the soil's capacity to store water while significantly reducing water runoff. They also need little long-term maintenance after they are established. Because natural landscapes do not require mowing or much maintenance, they reduce the need for gas-powered lawnmowers, which add carbon from the burning of fossil fuels, while native plants sequester carbon from the air. Native plants provide habitats and food for native animal species such as birds and butterflies, encouraging biodiversity.

Drip irrigation (*DI*): Drip irrigation is the gradual application of water to the plants' root zone. It is more efficient than watering the surface because water is not wasted on nongrowth areas, there is less evaporation and runoff while the plant root zone is maintained at its ideal moisture level, encouraging deeper roots.

Low-flow fixtures (*LF*): Potable water is a precious resource that is available for human consumption in very limited quantities. Furthermore, water consumed in buildings also generates CO_2 emissions because it usually takes energy to move and treat it. The farther this water must be transported and treated for human consumption, the more energy is used, generating more emissions. Students estimated water consumption in the building and then implemented measures to reduce its consumption through various conservation measures such as installing sensors and flow restrictors on water fixtures.

Dry fixtures (*DF*): A more drastic method to reduce the use of water in buildings is installing dry fixtures such as composting toilets and waterless urinals. Composting toilets

use a small amount of water saving the energy of treating wastewater, and eliminating nutrient release into the watershed. An example of a composting toilet is the system at the Bullit Center, in which human waste is treated and begins its aerobic process of decomposition in one of ten composting systems, each about 84″ tall × 40″ wide × 61″ deep. The liquid and solid matter is mixed with wood chips and fluffed regularly using tines, or comb-like structures that can be turned using a special socket wrench. As the matter decomposes, the particles become smaller and smaller, and naturally filter down toward the bottom of the pile. Successful compost requires oxygen to keep the pile from going septic, or turning anaerobic. The required air is actually drawn through the toilets themselves then down the waterless pipes. To make sure that oxygen is permeating the pile, the amount of liquid is carefully managed, and spread evenly among the piles. Excess liquid is pumped into leachate storage tanks in an adjacent room that maintains a strictly aerobic decomposition process, eliminating the release of methane gas and odors, by-products of typical waste treatment. The composters yield three products: carbon dioxide, stabilized leachate, and biosolids (http://www.bullittcenter.org/building/building-features/waste-not/#sthash.T3L0tUjd.dpuf).

Gray water reuse (*GW*): Gray water is water that has already been used in the building but does not contain harmful pathogens from feces. It is typically wastewater from clothes washers, baths and showers, kitchen sinks, dishwashers, and lavatories. In some municipalities, only wastewater from clothes washers is permitted to be used as gray water. If properly collected and stored, gray water can be safely reused, mostly for plant irrigation, reducing consumption of potable water and the load on septic tanks and leach fields. If gray water goes into rivers, lakes, or estuaries, its nutrients become pollutants, but to plants, they are fertilizers. Gray water should not be sprinkled and should not be used to irrigate edible plants. It is also important to use "plant friendly" products, without salts, boron, or chlorine bleach that could kill the plants being irrigated. Gray water should not be stored for more than 24 hours because its nutrients could start to break down. The wastewater generated by toilets is called black water. There are also natural systems that clean black water using biological instead of chemical processes.

Rainwater harvesting (*RH*): Harvested rainwater is captured from the roofs of buildings and can be used for indoor or outdoor needs. Harvesting rainwater reduces the consumption of treated potable water, thus reducing a building's impact on the environment and its carbon footprint. Figures 3.59 and 3.60 show student proposals for New Orleans with different types of rainwater harvesting systems while Figure 3.61 shows a proposal for a California highway rest center in which the collection of water is one of the dominant design features. The next two images show a student project for single-family homes in Los Angeles that collect more water than they use utilizing multiple collection surfaces and water treatment and gray water systems (Figure 3.62). Even though the idea is hypothetical and the cost to build such a solution is prohibitive, the concept is important; if more of these homes were built in Los Angeles, they would slowly rebuild aquifer and water reserves (Figure 3.63).

Generate energy from methane (*MT*): Waste in a landfill generates methane, which can be used to generate energy. The EPA requires all large landfills to install collection systems to minimize the release of methane. These gases are collected by drilling "wells" into the landfills and collecting the gases through pipes and combining them with natural gas to fuel conventional combustion turbines or used to fuel small combustion or combined cycle turbines. Landfill gas can also be used in fuel cell technologies, which

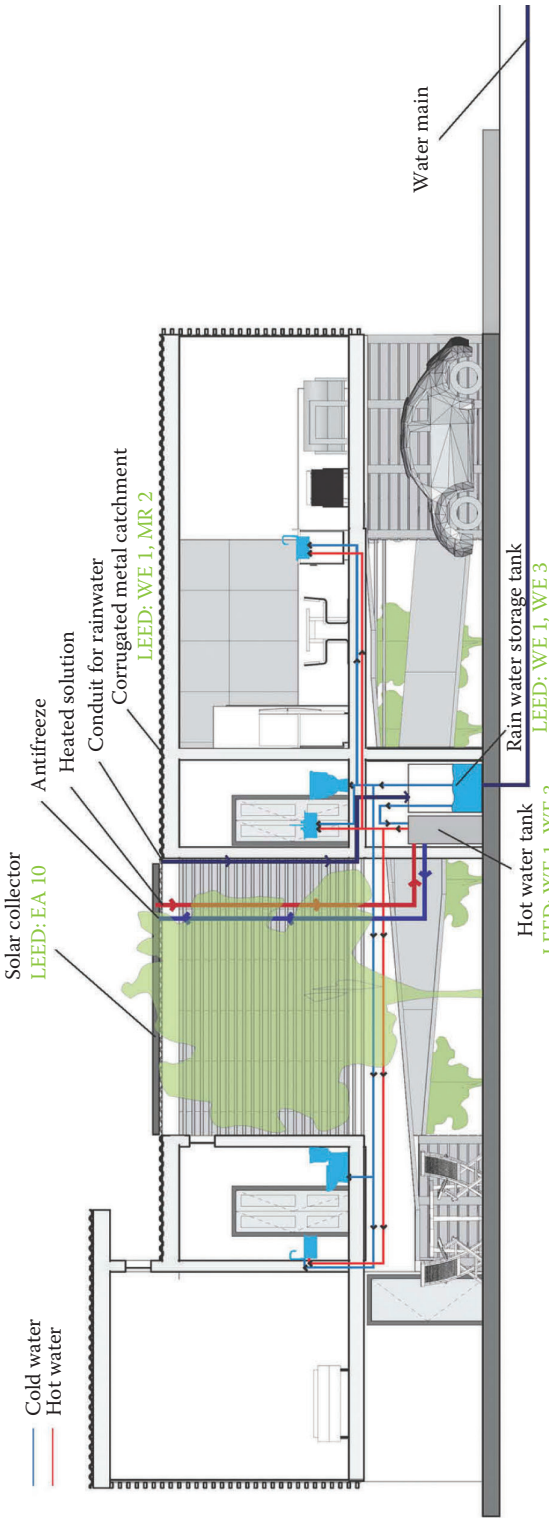


FIGURE 3.59 Water system and rainwater harvesting. (Courtesy of Cal Poly Pomona student Leslie Cervantes.)

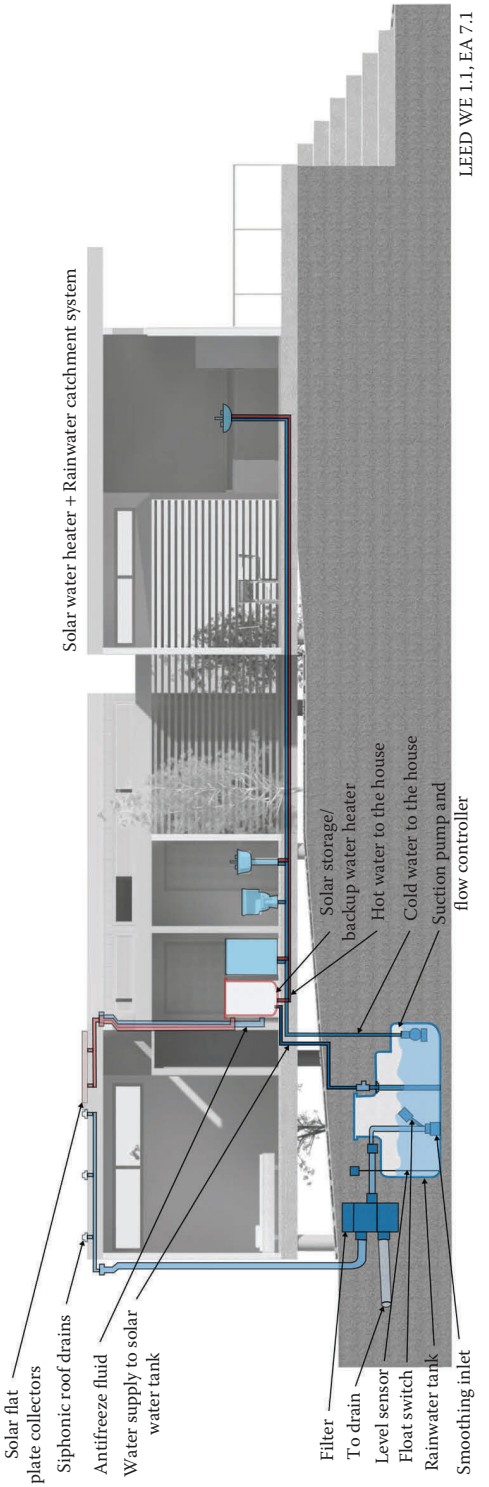


FIGURE 3.60 Water system and rainwater harvesting. (Courtesy of Cal Poly Pomona student Jillian Schrotinger.)

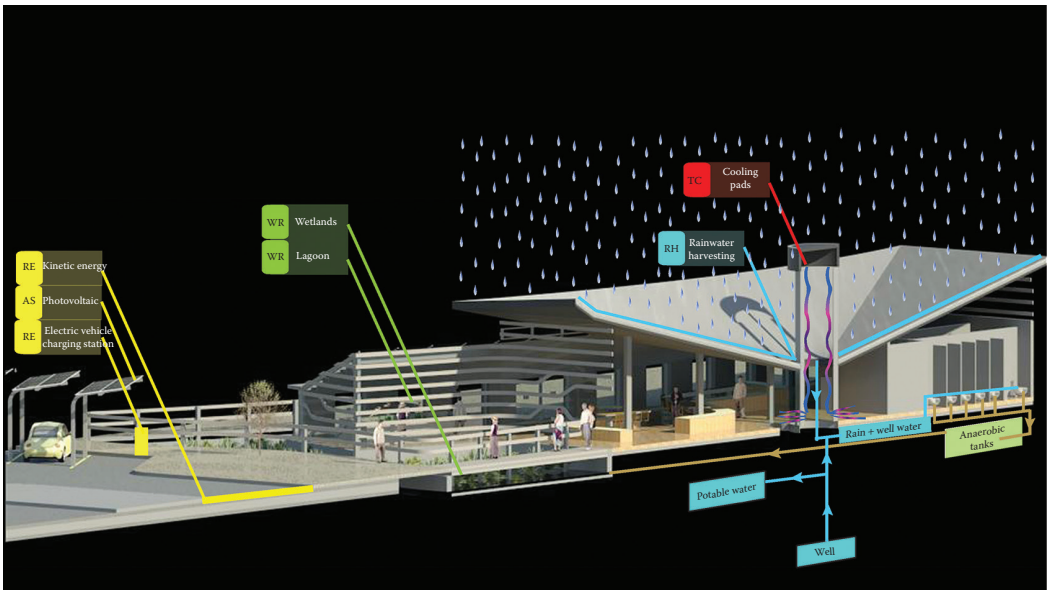


FIGURE 3.61 Water strategies in a California Rest Center. (Courtesy of Cal Poly Pomona student Benny Yeh and Blaise Fremont.)

use chemical reactions to create electricity and are much more efficient than combustion turbines.

Composting (*CM*): Composting is the aerobic, biological decomposition of the organic constituents of waste under controlled conditions. Some heat is liberated during the process, causing the compost to warm. During aerobic composting, microorganisms consume organic material; nitrogen is used by these microorganisms for metabolism and cell growth, while carbon supplies an energy source. Some materials such as kitchen scraps provide nitrogen, while other materials such as leaves and dried straw provide carbon. The rate of composting depends on a number of factors, but most important are moisture content, carbon-to-nitrogen ratio, aeration, temperature, and microbial population. The end product of composting is a dark, crumbly substance. Because the volume of the material is reduced to a quarter of its original size, composting is an excellent way to recycle yard and kitchen waste while reducing the volume of waste sent to landfills. In addition to these benefits, the energy that is produced as a by-product of the composting process can be used to heat a space. Student Perry's tests at the Lyle Center for Regenerative Studies at Cal Poly demonstrated that it is possible to heat a space with the waste heat generated during the composting process. During her tests, which she monitored for a period of 30 days, a 3-gal container reached a temperature of 160°F and an average of 118°F. Perry estimated her small composting pile to generate 2500 Btu/hr of heat at peak capacity.

Recycling (*RC*): Recycling reduces the amount of solid waste that we generate and the amount of GHGs. According to the EPA (2011) recycling reduces emissions from energy consumption, reduces emissions from incinerators, reduces methane emissions from landfills, and increases storage of carbon in trees. The EPA estimates that increasing the U.S. recycling rate from its current level of 27%–35% would reduce GHG emissions by 11.4 million metric tons of carbon equivalent over landfilling the same material.

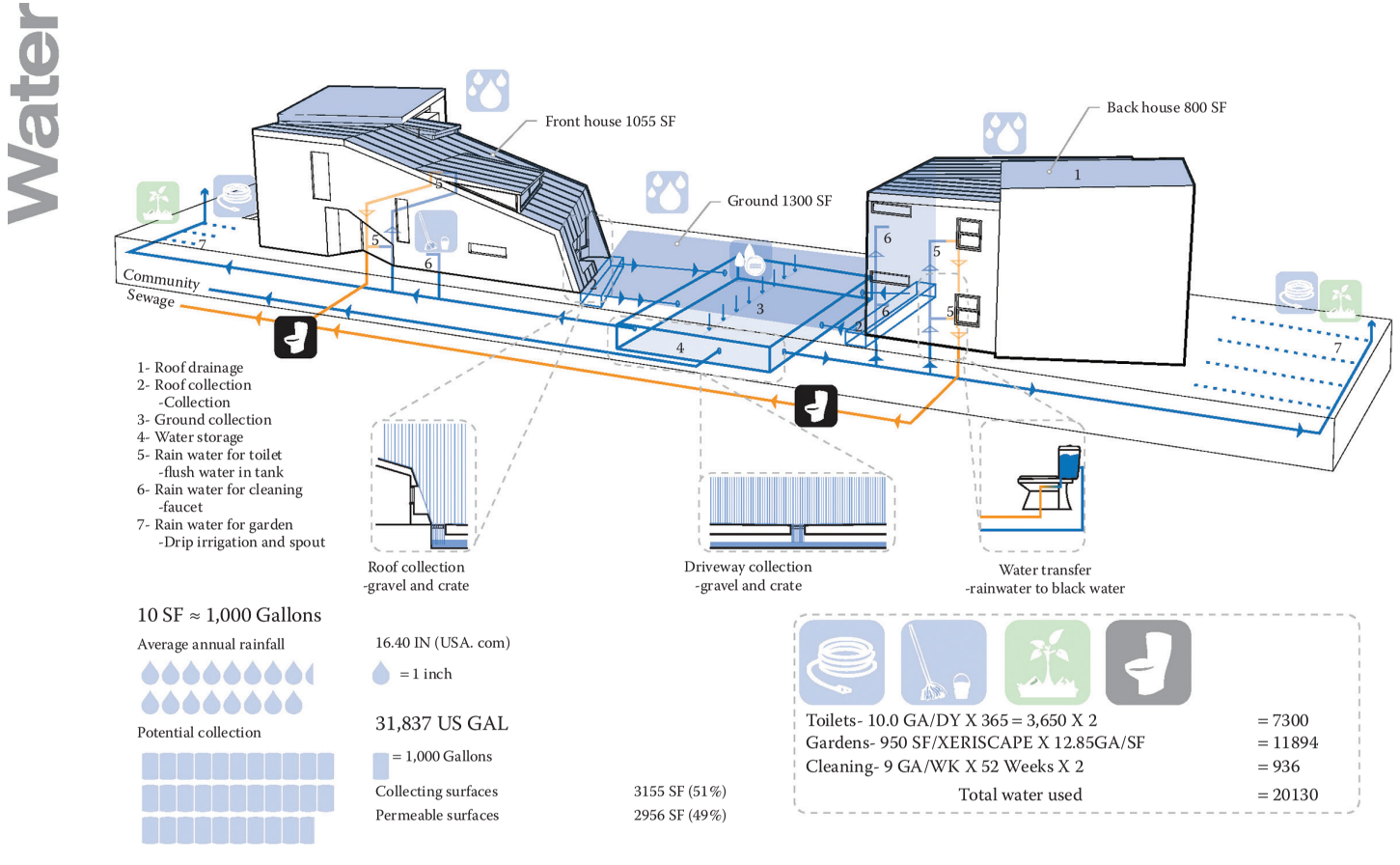


FIGURE 3.62 Residential water system. (Courtesy of Cal Poly Pomona students Calvin Huang and Mathew Trujillo.)

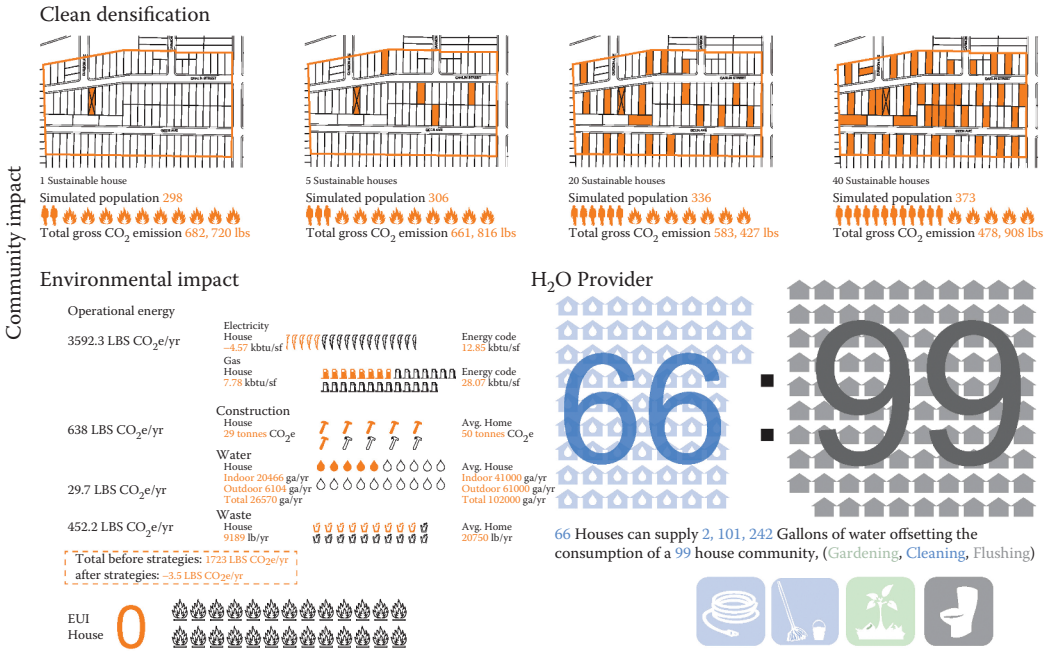


FIGURE 3.63 Residential water system. (Courtesy of Cal Poly Pomona students Calvin Huang and Mathew Trujillo).

3.3 DESIGN AND PRACTICE: THE PAMO VALLEY PROJECT

It is important to link academia and practice so that student experience is enriched with real-life constraints while practitioners are also infused with fresh, sometimes out of the box, ideas from young designers. Most of the design studios previously mentioned have some component of integration with practice. The following experience will be discussed in more detail as an example of integration between teaching and practice to achieve low-carbon buildings.

During the 2007 California wildfires, 1350 homes were destroyed or damaged, 300,000 acres were burnt, and 15 people died in San Diego County alone. These fires affected the entire state of California; the governor declared a state of emergency in seven counties, and the president ordered federal aid to supplement local response efforts. The 2007 San Diego County Witch Creek fires claimed 197,000 acres and destroyed over a thousand homes. Among those devastated were two homes in Pamo Valley, owned by the City of San Diego but leased by ranchers who maintain the land, thereby making them eligible for FEMA (Federal Emergency Management Agency) emergency assistance funds (Figures 3.64 and 3.65). The City of San Diego departed from convention by deciding not to purchase FEMA trailers for the ranchers and instead decided to contact Cal Poly Pomona for an alternate solution. While traditional FEMA trailers have been helpful in the past, their one-size-fits-all application dismisses valuable opportunities for sustainable solutions, ignoring our increasingly environmentally sensitive culture. The trailers' generic and predetermined character also renders them incapable of acclimating to the unique environment of a given site. The city decided to use funding from the FEMA for Cal Poly Pomona students to design two homes to replace those destroyed in Pamo Valley.

Disaster relief commences with the immediate rescue effort and transitions toward an eventual return to normality. Everyone involved in the process must adapt. Victims must adapt to the loss of their homes and the familiarity of their lives. However, solutions must evolve beyond temporary emergency shelter. The Pamo Valley Project serves as a notable example of a tailored response to the aftermath encountered by a community devastated by fire and inspires others to form community

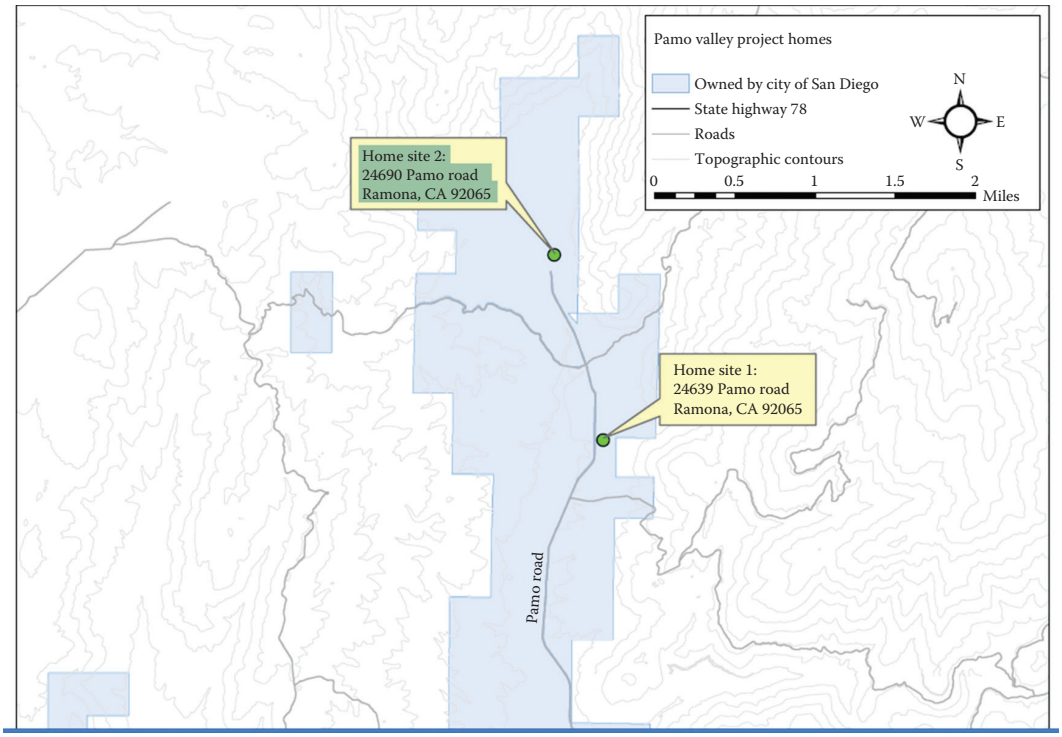


FIGURE 3.64 Pamo Valley house sites.

FIGURE 3.65 Pamo Valley view.

alliances that can be expanded into larger contexts. The Pamo Valley design solutions are context sensitive and harness the site's specific environmental conditions. Daylighting, natural ventilation, water harvesting, waste management, and alternative energies provide a self-contained living space ideally suited for disaster areas where electricity, gas, and water services are intermittent or unavailable. Although these projects are built to be site specific, the Pamo Valley houses could easily serve as an adaptable prototype for other locations. These prototypes could also be used in other fire-affected locations in Southern California so they had to cost less than a FEMA trailer and be easy and quick to build.

The Pamo Valley initiative received a grant by the National Council of Architectural Registration Boards (NCARB) in 2010. The grant supported the development of a co-lecture classroom environment shared by practice and academia using the Pamo Valley Project as a case study. The goal was to integrate community, business, and student efforts and evolve how the architecture profession approaches disaster relief. Ideally this collaboration would eliminate traditional roles in architecture while encouraging community involvement and cooperation. The Pamo Valley Project bridges concepts of the practice academic model and transdisciplinary methods to form the transdisciplinary practice initiative (TPI), a pedagogical shift that supports a co-lecture classroom environment between practitioners, scholars, government agencies, and the community. The TPI is organized into four phases: evidence-based design, paid internship, construction, and postoccupancy analysis. The initiative brings to the forefront the value of integrated education and the responsibility and accountability of future professionals.

Working in a carbon-neutral studio during the winter of 2010, 23 students worked in teams to create 11 proposals. A primary goal was to demonstrate that eco-friendly design does not have to be difficult or expensive. Participants were tasked with designing resident-sensitive homes that embrace core sustainable strategies and augment passive and active system performance—strategies that FEMA trailers cannot facilitate. Students were also to create projects with a sense of place that would encourage pride of ownership. The City of San Diego expressed interest in design aspects emphasizing fire resistance, blending with the environment, reasonable cost, and the possibility for replication. Students were to achieve these design objectives within a reduced carbon footprint and a significant energy use intensity reduction. Analysis of climate-specific conditions supported implementation of passive strategies to achieve thermal comfort, and adequate illuminance levels were achieved using energy modeling and carbon counting tools. During this studio, practitioners from local firms worked in tandem with faculty in the university classroom and studio time was divided in three parts: faculty instruction, practitioner instruction, and studio integration where both faculty and practitioners engaged in one-on-one discussions with student teams. In the studio integration phase, students balanced design issues with energy simulation tools using a carbon-neutral protocol developed by the author to design low-energy, low-carbon prototypes (La Roche, 2012). As is typical in design studios, students also presented their designs to their peers, faculty and collaborating practitioners. Two projects were selected to carry over to the spring seminar (P+Dzn by Dimitrios Tolios and Parinaz Behbahani, and MOD5 by Brandon Ro and Aaron Locke). These designs successfully incorporate carbon-neutral strategies to reduce emissions from energy use, construction and waste, and provide feasible solutions for adapting inexpensive and environmentally responsible architecture to disaster relief.

$P + D_{zn}$ was inspired by the vernacular aesthetics of the houses destroyed in the fires, at a low cost, high delivering carbon neutrality within the confines of the budget (La Roche and Tolios, 2011). The modular construction combines flexibility (Figures 3.66 and 3.67) and low waste production, while the highly insulated, air-tight envelope design provides comfort for residents even with the wide temperature swings common in Pamo Valley (Figure 3.67). The solar roof interfaces with the HVAC system, providing passive heating and cooling, supporting a net-zero carbon performance, and organizing their carbon-neutral design process and strategies to achieve minimum emissions (Figures 3.68 and 3.69).

FIGURE 3.66 Building design. (Courtesy of Cal Poly Pomona students Parinaz Behbahani and Dimitrios Tolios.)

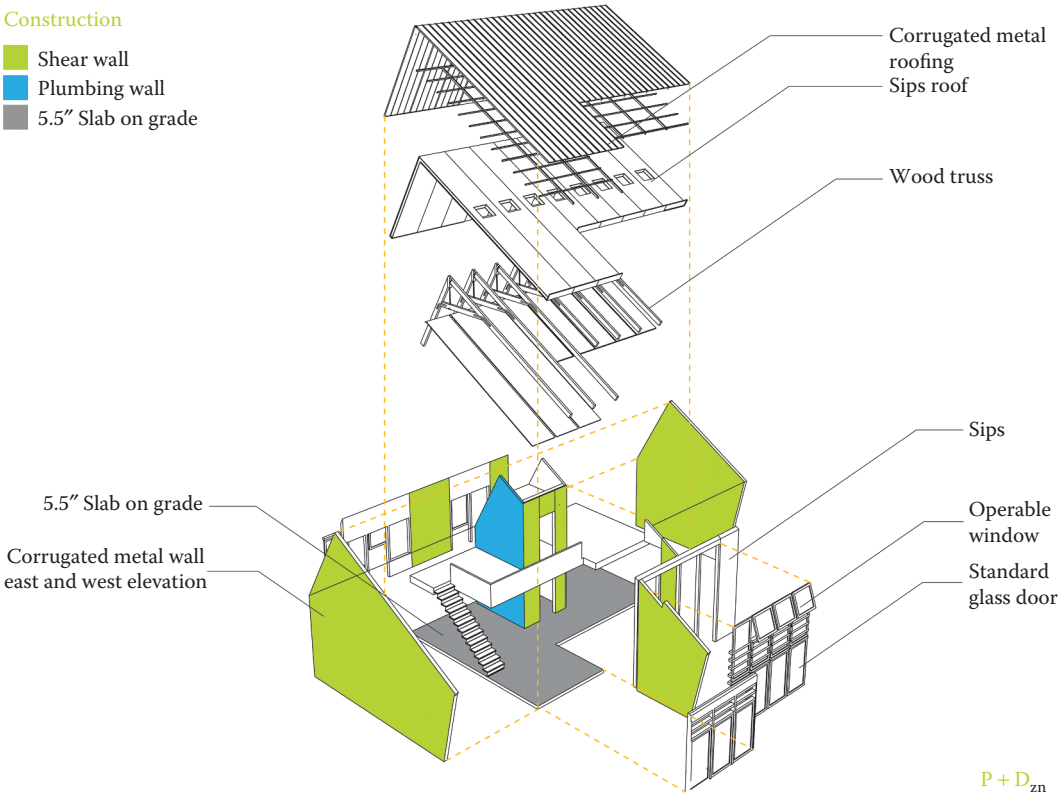


FIGURE 3.67 Construction system. (Courtesy of Cal Poly Pomona students Parinaz Behbahani and Dimitrios Tolios.)

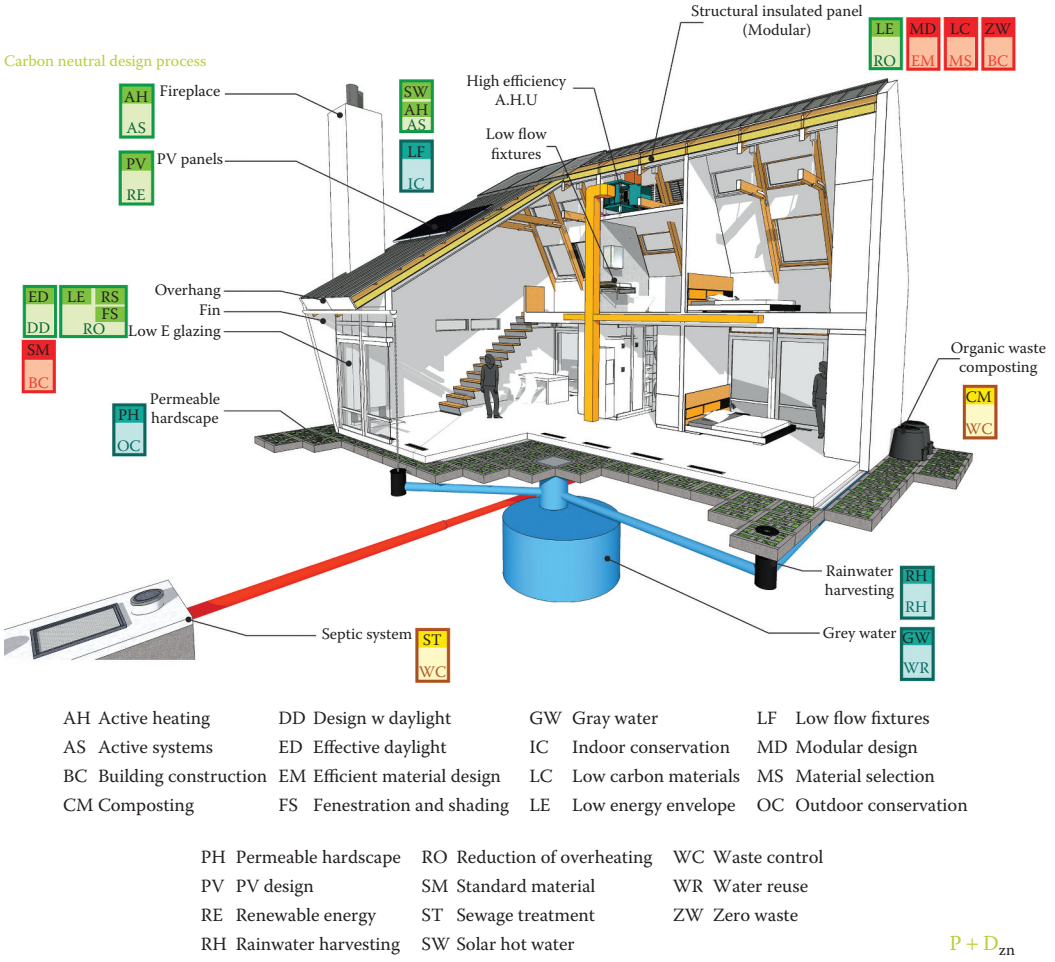


FIGURE 3.68 Carbon-neutral design strategies in building. (Courtesy of Cal Poly Pomona students Parinaz Behbahani and Dimitrios Tolios.)

The modest, elegant MOD5 house utilizes passive and active climate control systems that create a comfortable, livable, and sustainable environment (Figure 3.70). Durable and cost-effective construction includes modulated and prefabricated materials, integrated with reclaimed and recycled resources to achieve a cohesive end result. The "flex wall," a manual system of moving panels, successfully implements the desired passive design strategy, reducing heat exchange during the day and during various seasons, as well as maximizing natural light (Figure 3.71). Sliding louvers enclose the house at night, while still allowing ventilation. Insulated panels can also be used to increase the *R*-value of the wall. The relatively small floor plan expands into the landscape, with usable deck space for both leisure and work activities. The interior capitalizes on built-in furniture and an open floor maximizes usable space (Figures 3.72 through 3.75).

Development and experimental research and testing of the different systems proposed by the students in the studio continued in a research seminar in the spring of 2011; students fabricated full-scale physical prototypes and evaluated systems proposed by students in the design studio in the previous quarter. The Lyle Center for Regenerative Studies at Cal Poly Pomona served as the test center for collecting real-time data used to verify system performance. Among the systems

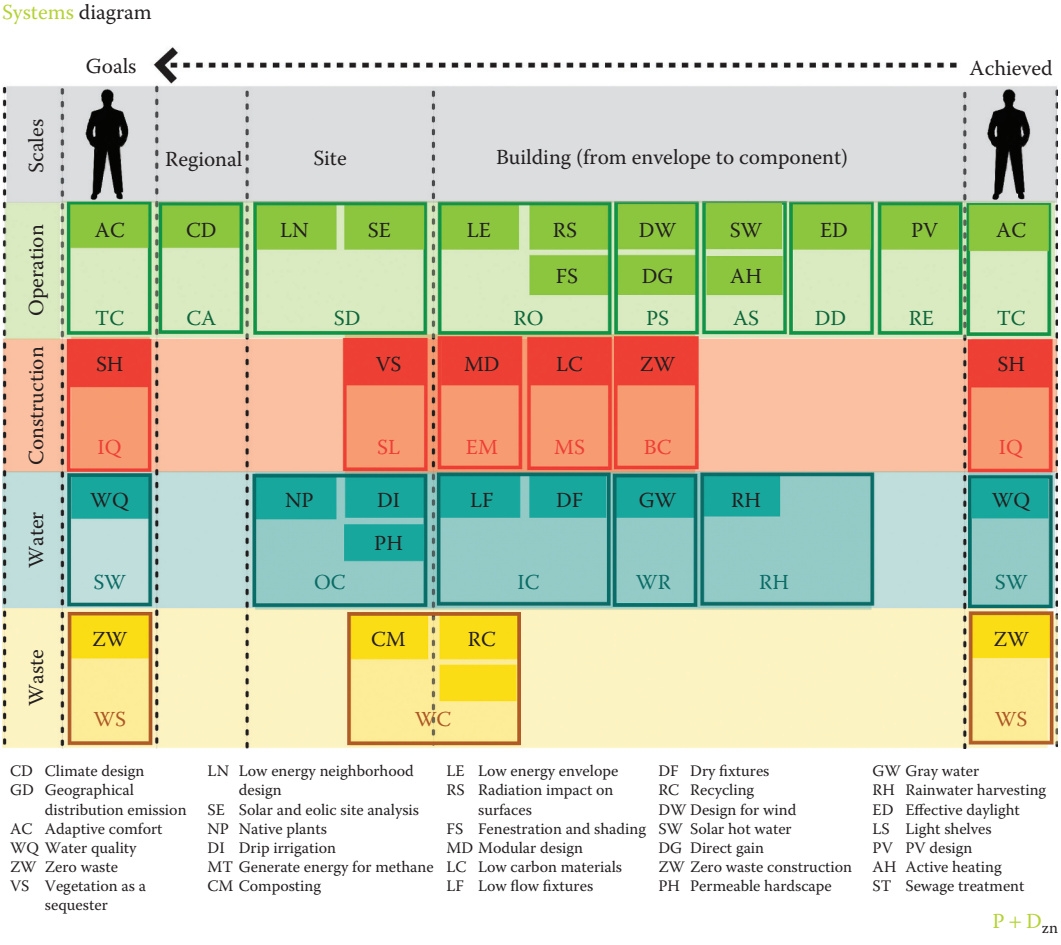


FIGURE 3.69 Carbon-neutral design strategies diagram. (Courtesy of Cal Poly Pomona students Parinaz Behbahani and Dimitrios Tolios.)

FIGURE 3.70 Building design. (Courtesy of Cal Poly Pomona students Brandon Ro and Aaron Locke.)

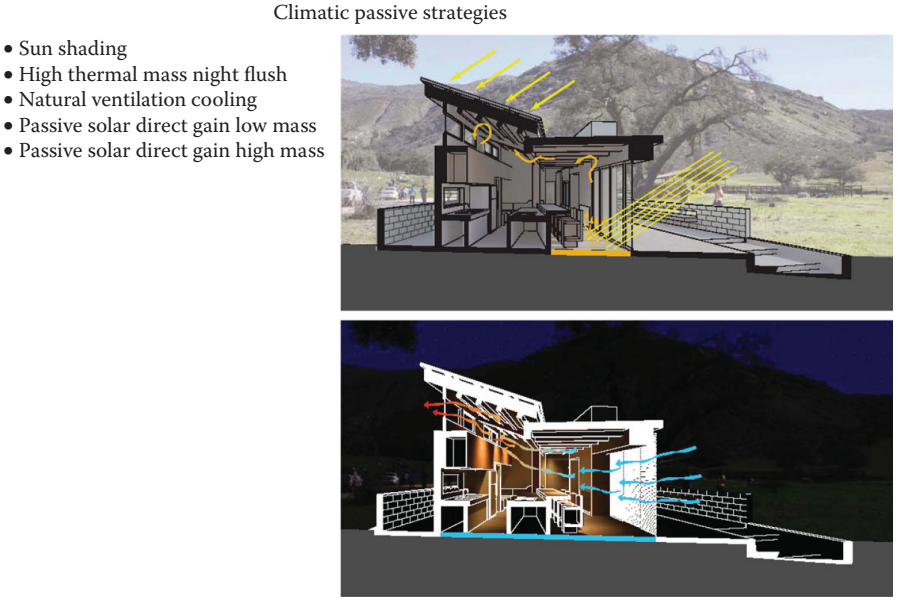


FIGURE 3.71 Passive strategies. (Courtesy of Cal Poly Pomona students Brandon Ro and Aaron Locke.)

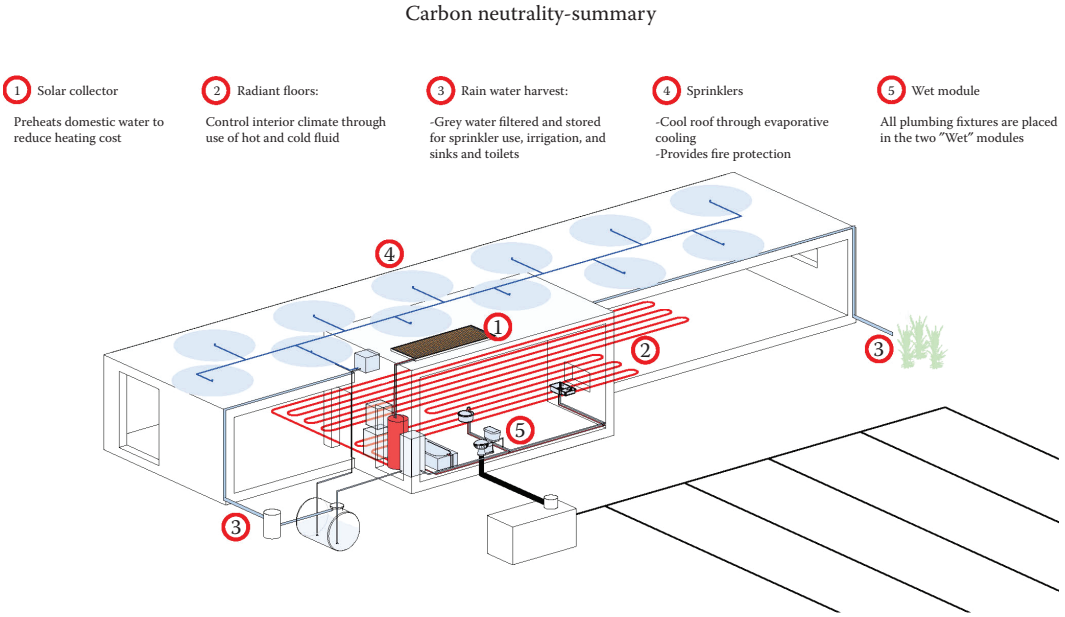


FIGURE 3.72 Design strategies.

tested was a water-cooled roof with night ventilation and radiant heating. Also tested was a double roof coupled with reversible direction fans, able to provide cooling in the summer and heat in the winter. This system continues the development of the system proposed by the students in the design studio (Figure 3.76). The students used the test cells at the Lyle Center to test the system against a control cell. Several series were tested, and each iteration improved performance. Figure 3.77 shows a system that combines evaporative cooling with night ventilation. Water is pumped from a

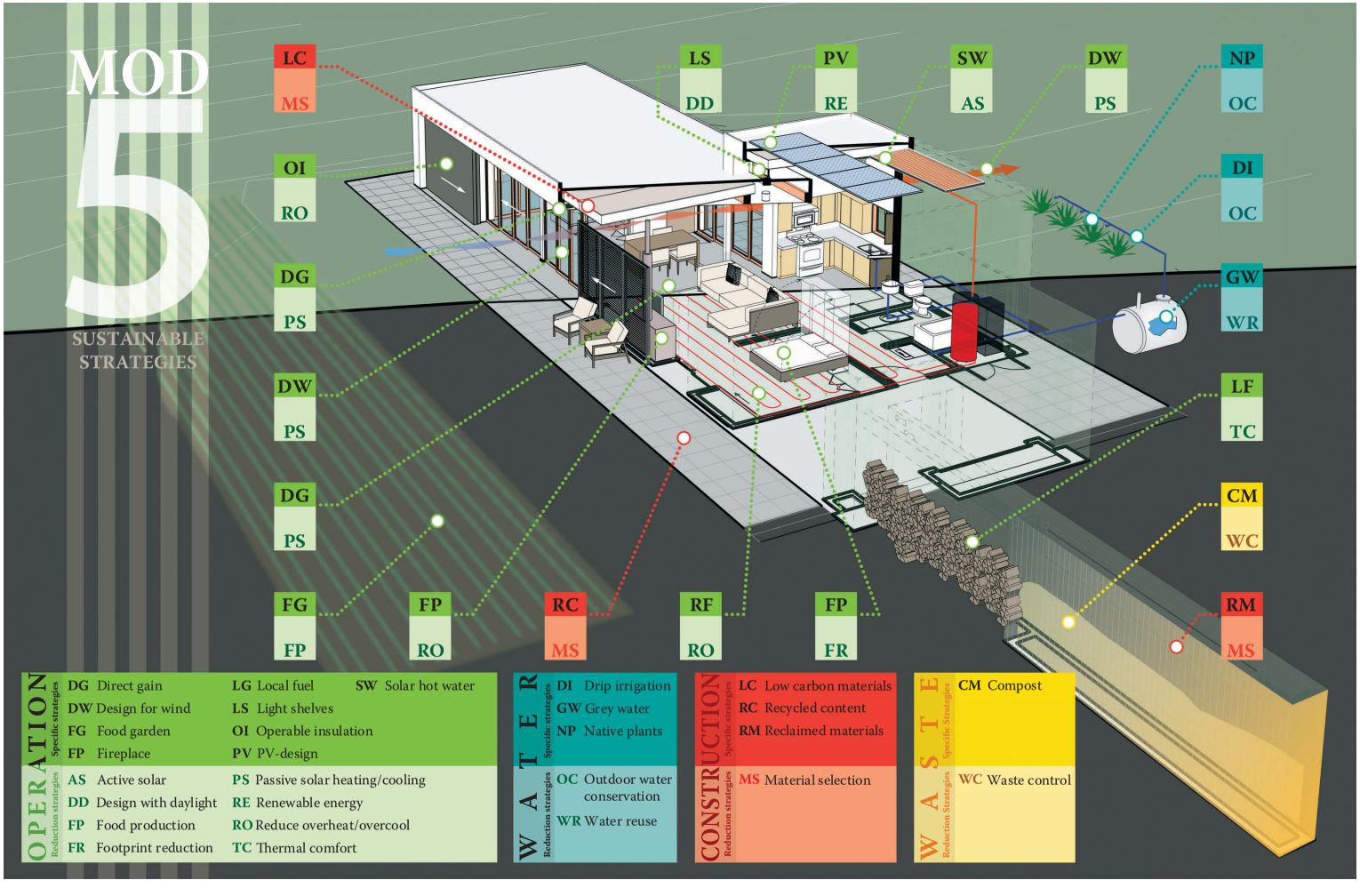


FIGURE 3.73 Carbon-neutral design strategies in building. (Courtesy of Cal Poly Pomona students Brandon Ro and Aaron Locke.)

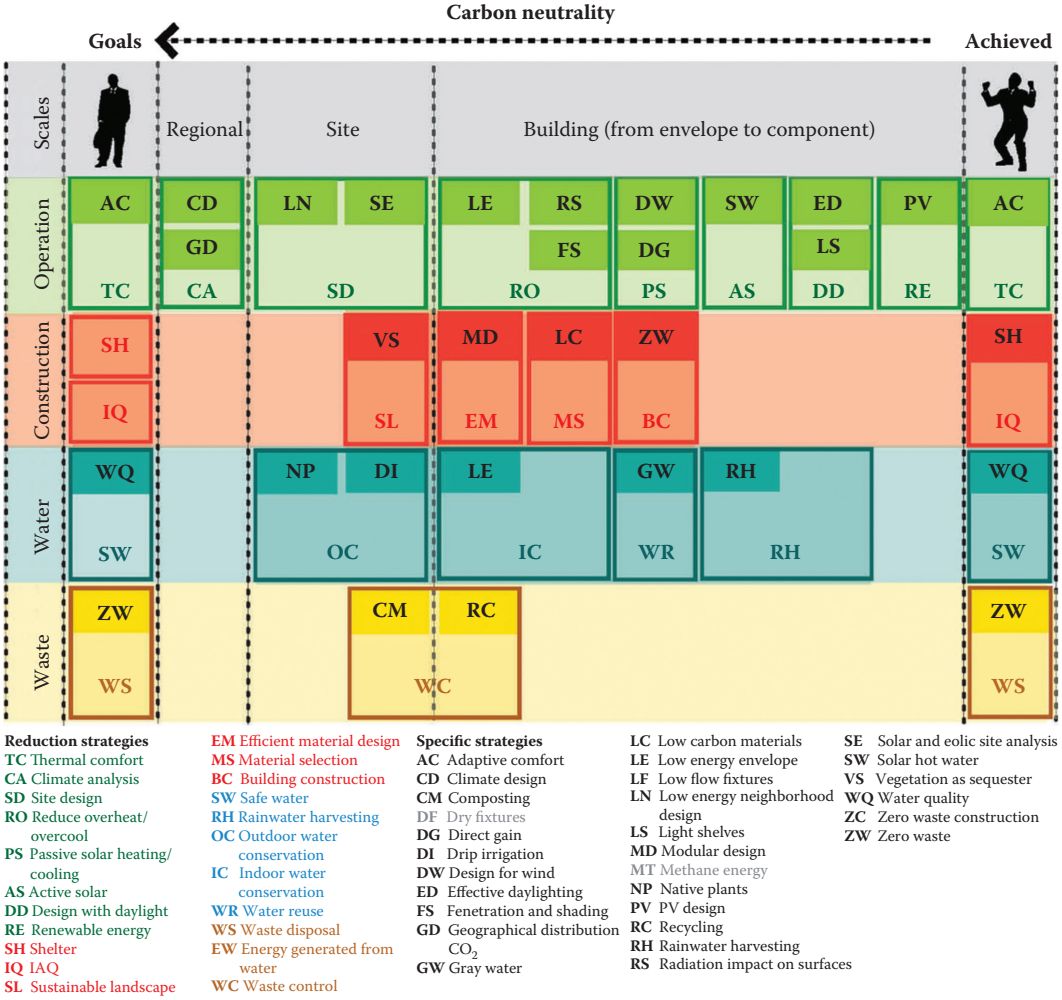


FIGURE 3.74 Carbon-neutral design strategies diagram. (Courtesy of Cal Poly Pomona students Brandon Ro and Aaron Locke.)

collection tank and is released in the roof by sprinklers keeping the upper metal roof and attic cool. This water is cooled by evaporation and runs down the sloped roof and is collected by a gutter system and stored in a tank (Figure 3.77). Several series were tested; in one for example, the sprinklers were activated when the attic temperature was higher than the interior and also higher than 79°F (Figure 3.78).

The in-depth and specialized research performed by the students for this project produced a usable model that can be used in architectural practice, which not only integrates sustainability with disaster relief buildings but also serves to integrate student learning with research and professional experience. Even though the projects were not built due to lack of funding, the project was developed all the way to construction drawings permitted by the city, demonstrating that it is possible to design low-cost, sustainable, alternatives to FEMA houses that are also adapted to local climate and conditions.

FIGURE 3.75 Poster with Mod 5 proposal. (Courtesy of Cal Poly Pomona students Brandon Ro and Aaron Locke.)

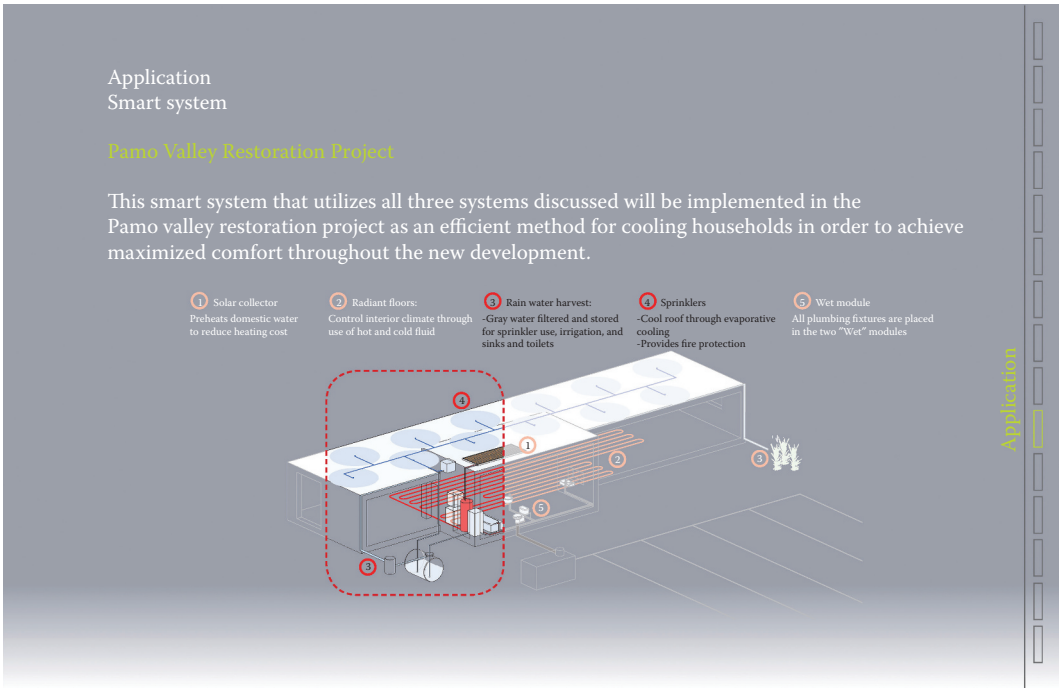


FIGURE 3.76 Cooling system developed as part of the studio project. (Courtesy of Cal Poly Pomona students Brandon Ro, Julie Coleman, and Gamaliel Aguilar.)

FIGURE 3.77 Hands-on work on construction of the system for testing. (Courtesy of Cal Poly Pomona Students Brandon Ro, Julie Coleman, and Gamaliel Aguilar.)

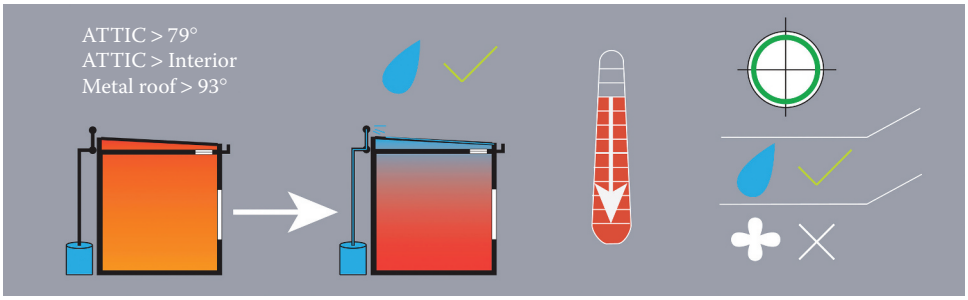


FIGURE 3.78 Example rule for evaporative cooling with night ventilation. (Courtesy of Cal Poly Pomona Students Brandon Ro, Julie Coleman, and Gamaliel Aguilar.)

3.4 DESIGN AND RESEARCH: THE GREENKIT

In many architecture programs there is a strong distinction between design-oriented courses or programs and research-oriented courses or programs. Both are important, and even more is important that future architects understand the importance of research in architectural practice. This section describes an experience that integrates research in the design of low-energy sustainable systems.

This combination of research and design courses was funded by a grant from the U.S. Environmental Protection Agency (EPA) P3 program. The P3 competition stated that current practices in building design have not provided a satisfactory balance among the three Ps, and aims to move the developed and developing world toward sustainability, building shelters that provide human comfort (*people*) using limited resources (*prosperity*) and minimum environment impact (*planet*). The purpose of our proposal, the GreenKit was to improve indoor comfort (*people*) while simultaneously reducing energy expenses (*prosperity*), dependence on fossil fuels and resulting generation of CO_2 (*planet*). These courses were part of a student-driven research project titled "The Green Kit: A Modular, Variable Application System for Sustainable Cooling" (Yezell, Felton, La Roche, and Fox, 2007) developed in a joint effort of architecture and engineering students working with local organizations in the United States, Uganda, Mexico, Venezuela, and China. It combined modular green surfaces and passive ventilation with computer controls to optimize the performance of these proven low-tech cooling strategies. It essentially was a smart window plus a green roof, with distributed sensing and embedded control (Figure 3.79). The resulting technology enabled dynamic management of ventilation and sun control in response to changing environmental conditions in real time. The GreenKit was intended for a broad audience of users, benefitting the individual homeowner by achieving thermal comfort at lower cost than a traditional cooling system, local economies by reducing the competition for nonrenewable fuels, and the entire planet though the reduction of global pollution.

During the 2006–2007 school year, students first gained an understanding of passive cooling strategies and green roofs while developing several smart window prototypes that could moderate solar radiation, daylight, and air movement, thereby maintaining occupant comfort within a building. The objective was to develop the smart window as an automated, self-powered cooling system that utilized both passive design strategies and low-tech actuators to respond effectively to real-time changes in temperature, sunlight, and wind conditions (Figure 3.80).

In addition to providing more comfort, the GreenKit reduces the cost and environmental impact of cooling with additional social and economical benefits. Both capital and operation costs would be lower, and with the exception of the microcontroller and sensors, the GreenKit could be built at low cost using local labor and resources in developed or developing nations.

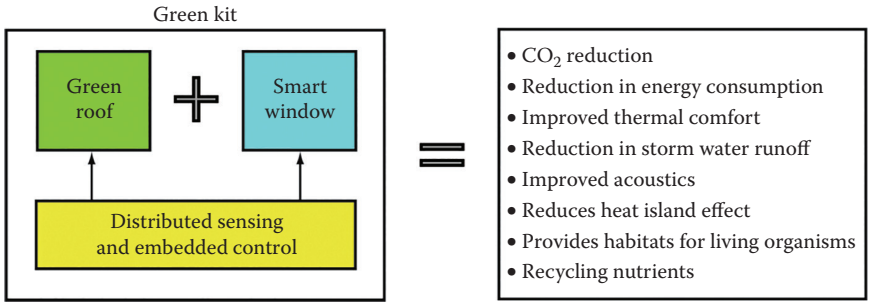


FIGURE 3.79 GreenKit components: Green roof, smart window, distributed sensing, and embedded control.

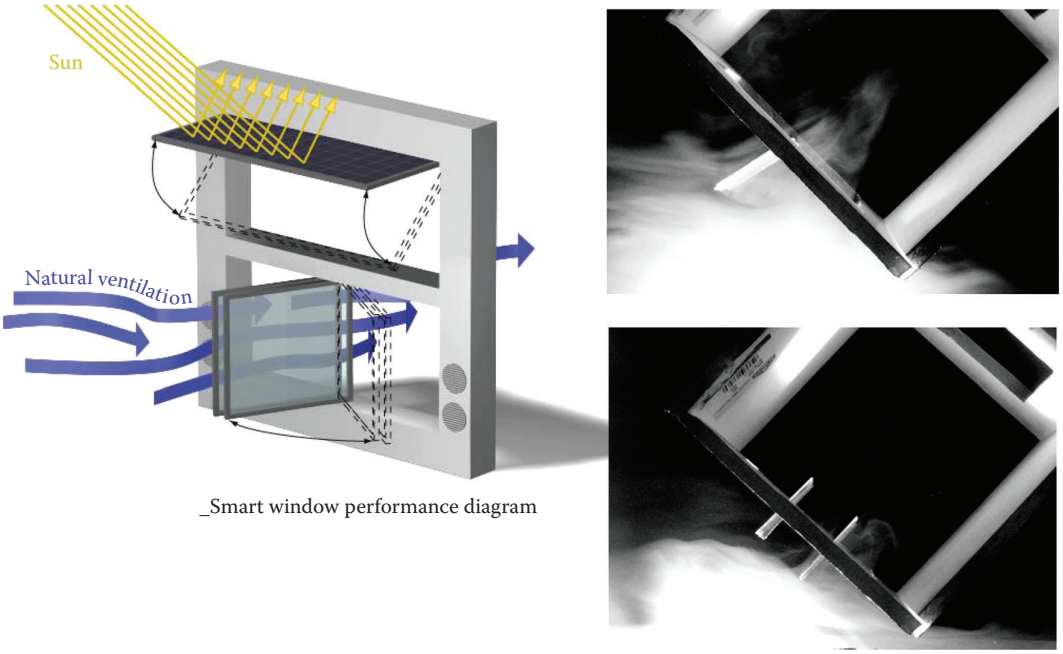


FIGURE 3.80 Smart window.

A green roof provides several benefits over conventional roofs: reducing storm water runoff, CO_2 levels, and solar loads inside the building.

The green roof consisted of an impermeable layer of plastic that works as a moisture barrier on top of the regular roof with "Cal Earth" bags above. These inexpensive bags of rice sack material were filled with a growth medium, which could be a mixture of native soil with vermiculite (to reduce weight), and placed in rows perpendicular to the slope of the roof (Figure 3.81). They allow water to filter through them while containing the growth medium.

The third component of the GreenKit is the distributed sensing and controlling system that optimizes the function of the other elements in the GreenKit. The smart window uses sensors to detect indoor and outdoor temperature, sun angle, wind speed, and occupant presence. The system responds to sensory input and operates the sun shade, wind scoops, and fans accordingly. An actuator control system operates the photovoltaic (PV) panel and the wind scoops. The PV panel provides power and shade from the sun, and the wind scoops promote ventilation to the

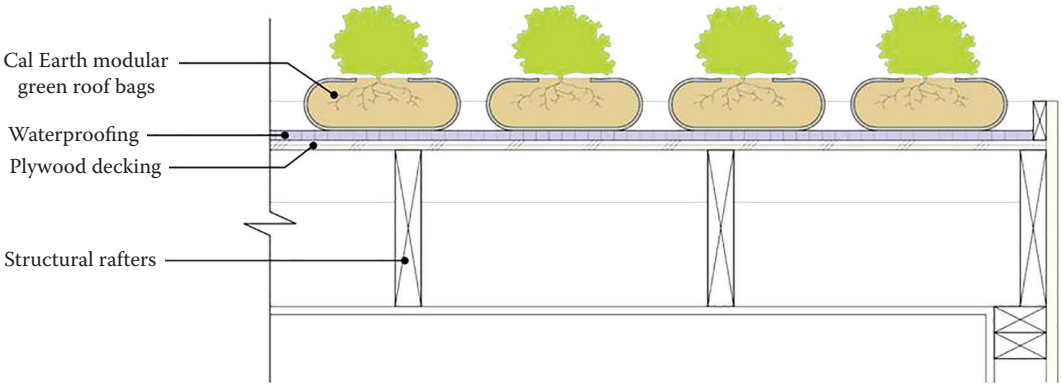


FIGURE 3.81 Low-cost green roof prototype for the GreenKit and Tijuana Housing prototype.

interior. The small fans can also be turned on for forced ventilation and night venting when the scoops must remain closed for security.

In the first design course, students designed projects (educational, residential, and medical facilities) incorporating the green roofs with the robotic systems. Several sites around the world were selected to develop socially responsible projects in developing and developed nations. They had to understand local culture, demographics, and climate data to initiate their design work. The building fabric and materials, together with the robotic system, interact with the environment to regulate external conditions and achieve thermal, acoustic, and luminous comfort. Students also developed the rules that would direct the robotic system to interact with environmental variables, especially the sun and the wind. The students had to use digital and analog tools to prove that their building designs worked. A simple wind tunnel was built and used to test airflow in buildings or parts of buildings. Shading and solar penetration was tested with different 3D modeling software, and energy performance was modeled using Home Energy Efficient Design (HEED) developed at UCLA. All projects included a green system, most of the time in the roof but sometimes in the wall, and an operable window with some level of control for multiple locations in the world. Among the projects were one in the Santa Rosa de Agua community in Venezuela (Figure 3.82) and a prototype for multiple locations in the Caribbean Sea (Figure 3.83), both with resilience in mind.

Reducing GHG emissions was a top priority for students in the GreenKit team. In 2007, an architectural elective class undertook the challenge of evaluating the systems and quantifying their performance by calculating their GHG emissions, compared to another building with a "typical" window and a standard air conditioner.

In the winter design studio, student teams developed and built five smart window component prototypes for integration into the GreenKit. These variations offered different strategies to improve upon a standard window. Concept one is a dual-layer, bifolding panel system. The interior and exterior panels operate independently of one another, which serves to maximize versatility. Concept 2 consists of a pivoting, three-panel system designed to track the sun and wind. The frame contains low-voltage fans for increased ventilation and a radiant heating system to reduce cold-air infiltration. Concept 3 has circular vents that shade as well as let in air that is evaporatively cooled by the vegetated surface. In the closed position, insulating vegetation makes this design unobtrusive. This concept is used in the design shown in Figure 3.83. Concept 4 consists of a rotating track that allows for maximum versatility according to real-time conditions. The panels follow the sun for optimized winter heat gain, summer shading, utilization of the PV overhang, as well as wind-tracking for optimization of wind scoops. Concept 5 has an accordion folding system with simplified, accessible mechanics. The system is designed

FIGURE 3.82 Housing in Santa Rosa de Agua Venezuela. (Courtesy of Cal Poly Pomona student Mark Lyles.)

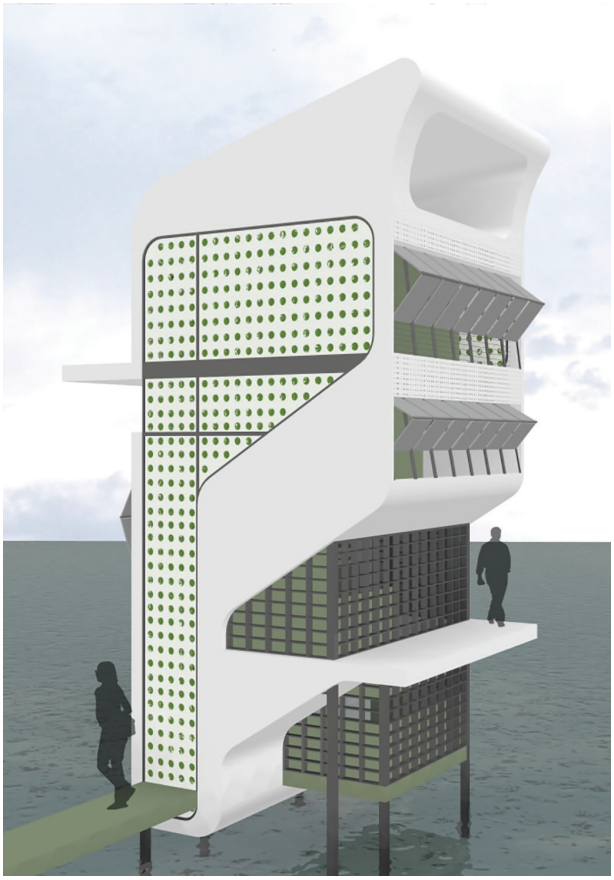


FIGURE 3.83 Resilient housing in Caribbean Sea. (Courtesy of Cal Poly Pomona student Stephen Nieto.)

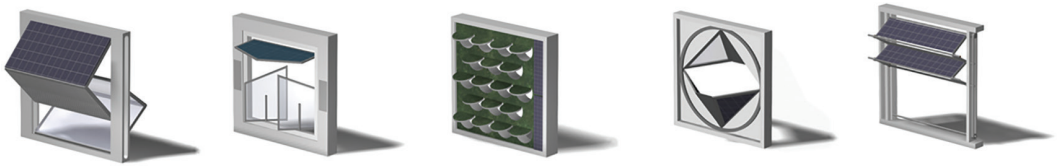


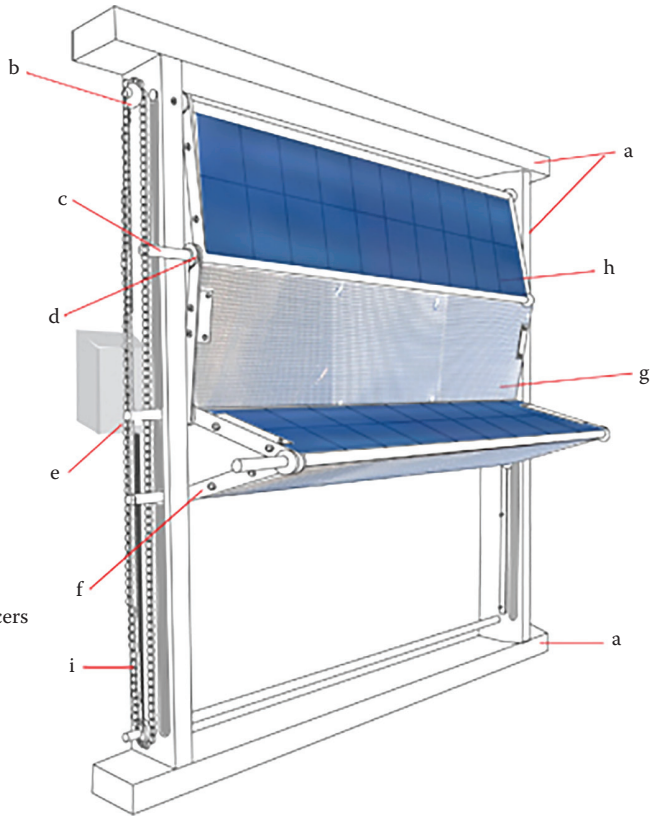
FIGURE 3.84 Window concepts numbers 1–5 (left to right) developed by students.

FIGURE 3.85 Window concepts numbers 1–5 (left to right) developed by Cal Poly Pomona students.

to work with one motor and is constructed from easily available materials, such as computer fans and a bicycle chain (Figures 3.84 through 3.86).

After the five robotic window systems were developed, a method was developed by the students to objectively evaluate each one and select the best option. This system, called by the students the PRIME (People, Responsive Interior, Materials and Environment) evaluation system (Figure 3.87), was loosely based on the layout of the system proposed by Malcolm Wells, and was developed as a methodological process by which the performance of each unit could be determined based on a scale of (−)2400 to (+)2400 (Epp, La Roche, and Fox, 2008). The performance of the unit was determined by its positive or negative effect on people, prosperity, and the planet. The PRIME checklist had three categories connecting the unit performance to the three Ps. In each of these categories, there are eight areas that receive scores from −100 to +100 and which are added by subcategory and by total. Higher values indicate better performance in all areas (people, prosperity, planet). Each of the variables in Figure 3.87 is compared to a *typical* window defined by the students. The "people" category was divided in two groups, people and responsive interiors. The first part addresses flexibility in design, potential to use unskilled local labor, easy-to-understand systems, and aesthetics. The second part dealt with thermal comfort, possibility for manual operation, seamless motion, and ability to enhance views. Prosperity is mostly focused on materials, water tightness, ease of maintenance, use of sensors, durability in general and in parts, use of locally manufactured parts, ease of assembly, ease of shipping or transportation, and simplicity in mechanics. Planet included the potential for implementation in a variety of climates, control of natural forces of the sun and wind, use of local materials and native plants, low embodied energy and long life span, passive comfort versus mechanical comfort, response to on-site climate change (adaptation), reduction of CO_2 levels, and generation of energy.

After all five groups of students presented their preliminary smart window designs, the PRIME system was used by *CPP faculty and students, as well as by faculty and students of the University of Texas via a digital feed to evaluate each one*. *Concept 5* (furthest to the right in Figure 3.85) was the *system with the highest score and selected as the GreenKit window component*. This design featured an accordion folding system with simplified, accessible mechanics designed to work with only one motor and was constructed using easily available materials.



(a) 2 × 4
(b) Tooth sprockets
(c) 1/2″ ∅Aluminium tube
(d) 1° × 1/2″ × 3/8″ Nylon spacers
(e) Servo motor
(f) 1/8″ × 3/4″ Flat aluminium for accordion folding element
(g) Perforated metal
(h) PV panel
(i) ANSI 25 roller chain

FIGURE 3.86 Window concept 5 further developed by Cal Poly Pomona students.

The strongest features of this design were its mechanical system and material selection. The simplified design of the mechanical system allowed for ease of maintenance and user override. Construction materials were selected for global availability. For example, the chain can be substituted with a common bicycle chain.

There were, however, four areas identified in the evaluation process of this window as needing further development. The PV panels located on the accordion shading system were not fully maximized, due to overlapping and nonparallel movement. There was also a concern that the depth of the overhang did not provide adequate shade from summer sun. Additionally, the vertical design of the accordion panels did not provide a way to capture the wind. Finally, the design relied on the inclusion of a secondary interior window for waterproofing. This meant that the component relied either on an additional mechanism or on user participation to open that window for ventilation.

These problems were solved using variations of successful elements from the other window concepts. These "borrowed" solutions include the half-panel photovoltaic from Concept 1 and the double wind scoop from Concept 2. By integrating the half-panel PV shade into the winning concept design, it solved the two problems concerning PV optimization and shade depth while maintaining the simplicity of the mechanical system. The wind scoops, redesigned according to wind tunnel testing, added increased control of indirect wind (Figures 3.88 and 3.89). After implementing these changes the component no longer needed a secondary window for waterproofing, solving the final concern.

PRIME Checklist for GreenKit evaluation

Project:

			−100 always	−50 sometimes	0 balances	50 sometimes	100 always	
People	People	Specialized design - too expensive						Flexible design for range of economies
		Specialized labor						Local labor
		System reactions unclear to user						Green kit system reactions educate user
		Ugly						Aesthetically pleasing
	Resp. Int.	Less comfort than window						More or better control of comfort than window
		Does not have manual override						Has manual override
		Disruptive motion blocks or interferes with view						Seamless and smooth motion allows or enhances view
Prosperity	Materials	Leaks in horizontal or vertical use						Water-tight in horizontal and vertical use
		Specialized maintenance/access						User maintenance/access
		Excessive or insufficient sensors						Appropriate use of sensors
		Degrades or has specialized parts						Durable or easy to replace
		Imported parts						Locally manufactured parts
		Specialized assembly						User assembly
		Bulky or awkward for shipping						Compact or easy disassembly for shipping
		Excessive or complicated mechanics						Minimal and simple mechanics
Planet	Environment	Benefits users in a specialized climate						Benefits users in a variety of climates
		Less management of sun/wind than window						Better management of sun/wind than window
		Imported materials and plants						Local materials and plants
		High embodied energy/short life span						Low embodied energy/long life span
		Needs mechanical heating or cooling						Maintains comfort level passively
		Does not respond to on-site climate change						Responds to on-site climate change
		Generates CO_2						Reduces/filters CO_2
		Consumes energy						Generates energy (PV panel)

−2400 max.		2400 max.

Final score:

FIGURE 3.87 PRIME evaluation system developed for GreenKit systems.

In conjunction with the initial PRIME evaluation system, students developed tests and analysis methods that helped to quantitatively evaluate criteria in each of the quadrants. These tests and analyses permitted further development of the smart window as well as quantification of the improvements. The shading and "wind tunnel" tests were essential in the redesign of the selected GreenKit. The results ensured a design that allowed for better management of the sun and wind than a typical punched window, and therefore more comfort, two of the main evaluation criteria. Students tested shading at four different latitudes and three different dates to

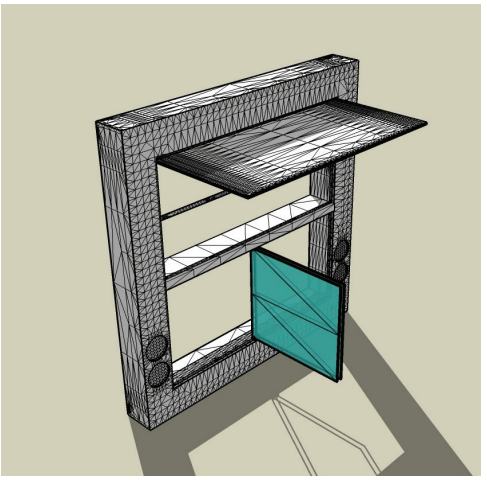


FIGURE 3.88 GreenKit window design.

FIGURE 3.89 GreenKit as built for the P3 exhibit at the National Mall.

determine the best angle for the PV panel for shade, view, and solar collection. A class-made wind tunnel analysis revealed that the most effective location for the wind flaps is in the center, perpendicular to the wall. Both of these tests proved valuable in refining the GreenKit's design.

Not only did the PRIME evaluation system provide an objective way of choosing the best smart window design, it also helped to develop the smart window by providing an easily understandable system that lists priorities and identifies the smart window's areas of needed improvement.

The P3 project received an ecomedia award and an honorable mention by the EPA and students published several papers, increasing their awareness of the impacts of buildings in the environment while providing an interdisciplinary experience with students and faculty from the electrical engineering department.

3.5 DESIGN AND SOCIAL RESPONSIBILITY: SHELTER WORK IN MEXICO

It is important to remember that sustainability is also about social equity. Students must understand that the road to carbon neutrality is not just energy modeling and technical calculations. It must also be grounded in social responsibility. It is not possible to have sustainability without social equality. Currently, sustainability is possible because there is an unequal relationship between those that have and those that do not have in the world. Truly carbon-neutral buildings will also be socially responsible. It is not possible to achieve carbon neutrality without social justice and improving the quality of life of those that have less. In addition to learning how to use the technical tools and software, it is also important that the students develop an understanding of this fact and a sense of ethics and social responsibility.

Cities of less developed countries are characterized by a very uneven distribution of income, amenities, and opportunities. Poverty has transformed many of these into infra-urbanized, informal, auto-generated spaces with a precarious and marginalizing pattern of urban development. Informal housing in these areas is usually self-built or built by local people without construction documents, generally lacking sanitary services, but more or less adapted to their immediate needs and desires, and with very low expectations. In less developed countries, more than half of the population usually lives in these informal settlements generating "cities" within cities that are larger than the formal sector. Formal housing in the informal sector developed by government agencies is not usually adapted to the requirements or desires of the families that will live in these communities. To increase the quality of these houses it is necessary to increase user participation in the design of their dwellings.

As living standards improve, people consume more of everything, including energy for heating and cooling. Cities, including those in less developed countries, are responsible for a large portion of GHG emissions; furthermore, they are undergoing important transformation processes that could increase their emissions but, at the same time, also offer opportunities to introduce alternative low-energy strategies and systems in new or existing buildings, which would be different from conventional mechanical heating and cooling systems operating in buildings of developed countries. The path to sustainable, low-carbon architecture does not have to be the same in all places and varies according to social, cultural, economic, and environmental differences. If HVAC systems are not common practice, it should be easier to implement alternative passive cooling systems. Passive systems already exist in traditional architecture, so improving their performance could help preserve endangered buildings, while the implementation of smart systems in new buildings would help to develop a contemporary architecture that maintains traditional values and is respectful of its environment. Social architecture empowers communities, reduces operating costs, and provides a healthier, safer, and more comfortable environment.

As with previous projects, a combination of design studios and seminars was implemented. Three strategies were incorporated in all studios: (a) digital and analog tools to evaluate performance, (b) student interaction with future occupants and clients, (c) deeper understanding of the site. An experimental research method was implemented in seminars implementing a process that followed the following steps: (a) research and precedents to learn basic concepts, (b) develop hypothesis, (c) design a system, (d) build the idea, (e) test the idea, (f) analyze data, and (g) generate conclusions.

3.5.1 Tijuana Affordable Housing Project

Sustainable technologies are incorporated into more and more buildings every day, but they are still out of reach of many low-income families. However, many traditional societies learned to build collaborating with nature, with an intuitive knowledge of the environment and climate, constructing buildings at a very low cost. In the development of this project we implemented strategies and systems based on proven traditional principles of sustainability, combining them with more advanced technologies that could be built at very low cost with local materials, providing adequate thermal comfort while being sustainable. A reduction in thermal performance was also acceptable if the cost reduction was significant.

FIGURE 3.90 Substandard housing in Tijuana.

Tijuana, Mexico, located just 20 km south of downtown San Diego, USA, typifies the environmental and social challenges facing the border region between the United States and Mexico. In the 20-year period between 1985 and 2005, Tijuana's population grew by an estimated 145%, to well over 1.3 million people (CONAPO—*Consejo Nacional de Población*). Much of this growth was the result of trade agreements between Mexico and the United States, stimulating industrial expansion along the northern border region of Mexico. This substantial growth has tremendous consequences to the region, particularly in terms of providing adequate housing for migrants moving into the area to pursue employment opportunities. As a result, many informal settlements have emerged in the foothills of Tijuana, comprising largely of substandard housing, with few urban services such as water and sewer, all in a severely degraded natural environment (Figure 3.90). Local residents have been quite resourceful in deriving shelter from readily available waste materials, such as tires, palettes, and garage doors. However, threats from criminal activity as well as natural hazards such as landslides, earthquakes, and floods present tremendous challenges for this informal housing sector. As of today, even with considerable progress in some areas, Tijuana, Mexico remains a poverty stricken area. It lacks the identity of a city and has a mixture of different cultures that have migrated north from different Latin American countries besides Mexico. Many end up staying in Tijuana because they cannot cross the border to the United States. As a result, those who decide to stay end up settling in land they do not own. Homes are created with just about any materials they can find, including garage doors, car tires, and wood pallets.

This project led by the author explored the development and integration of sustainable technologies for low-cost housing in Tijuana with integrated design, research, and construction in one project. The Tijuana house project was initiated as part of the Lyle Center's Habitat 21 initiative to achieve a just world in which all people live with dignity in safe, healthy, and environmentally sustainable habitats (La Roche et al. 2006).

Corazon is a U.S. nonprofit organization whose mission is to effectively serve the poor in Mexico through an active home-building program, educational programs, and other community development activities, serving impoverished neighborhoods in Mexican border communities. Corazon's home-building program is effective in providing much needed shelter for residents of the communities in which they work. Chief advantages of their designs include their low cost as well as relative

ease of construction, allowing unskilled volunteers to construct these units in a single day. However, because of cost requirements and the need for a quick and manageable construction schedule, their designs rely on imported, nonrenewable materials that increase the expense, do not adequately consider heating and cooling needs, and do not address issues related to shelter that affect public health and quality of life, such as water, sanitation, security, and food production. There are more sustainable approaches that could enhance quality of life for the homeowners. However, any truly viable solution would need to operate under the conditions faced by Corazon and other housing relief organizations: it must be affordable, easy to construct, and desirable for local residents.

To support Habitat 21's goals, a team of interdisciplinary faculty, staff, and students from Cal Poly Pomona received funding to aide in the development of prototype solutions for sustainable housing systems that met the needs of relief organizations as well as local inhabitants. Working within the parameters of the Corazon home-building program, the team designed and tested prototypes that emphasize materials readily available within Tijuana, technologies appropriate for the cultural and economic conditions of the community, and strategies that minimize the use of energy, or other expensive resources. This includes passive heating and cooling technology to increase human comfort and minimize energy costs, addressing security concerns of residents, exploring affordable food production alternatives for residents, and addressing water and waste systems to protect public health. The project explored the integration of specific technologies to examine their interdependency and reciprocal contributions. A driving motivation for research was the examination of how outputs from one system, including waste, could become a resource for another system. The team included expertise from the fields of architecture, engineering, landscape architecture, plant science, urban planning, international development, anthropology, and geography. Students also built a full-scale prototype of the house at the Lyle Center in which several low-cost sustainable

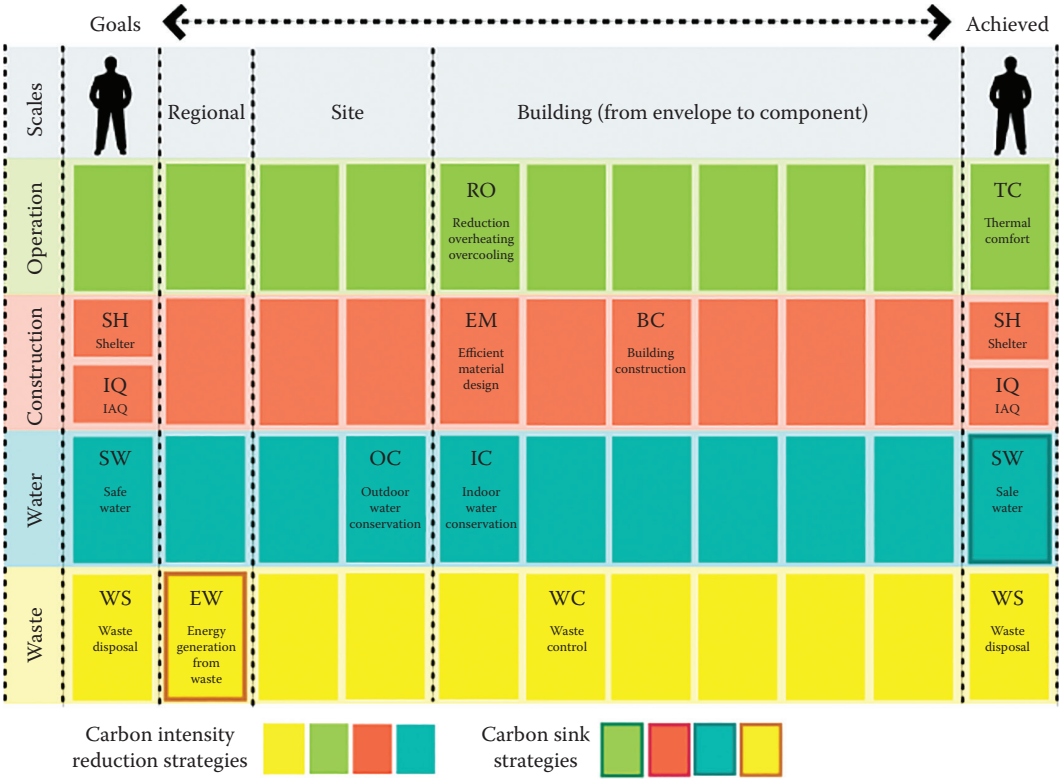


FIGURE 3.91 Carbon-neutral design process in the Tijuana prototype.

systems have been monitored and tested. Figure 3.91 shows some of the strategies implemented in the project in the carbon-neutral design process diagram.

The climate of Tijuana is temperate, moderated by the Pacific Ocean, without extreme winters or summers. Maximum average summer and winter temperatures are 30.3°C and 22.7°C, respectively, and minimum average summer and winter temperatures are 18.4°C and 5°C, respectively. Relative humidity is typically between 50% and 65%. Many winter nights have very clear skies, increasing radiant losses from the building to the night sky. Interior temperatures at night follow exterior temperatures quite closely, easily reaching close-to-freezing interior temperatures during many winter nights. Nevertheless, none of the houses in the colonias have heating systems or insulation. This is not only uncomfortable for the dwellers but also dangerous, especially for children and the elderly. Occupants complain of the cold at night and do not always sleep in the bedroom, instead searching for the warmest part of the house, using many blankets and sweaters to try to keep warm during the night. An analysis of the hourly temperatures using the climate data for San Diego, just a few miles north, indicates that thermal comfort can be achieved inside a building during almost every hour of the year using passive means. Passive solar heating could be implemented in the winter, and night ventilation with thermal mass or daytime ventilation could be implemented in the summer.

The house had to be very low cost and sustainable, providing conditioned spaces and security for the residents while being easy to build using local materials and labor, integrating indoor and outdoor spaces to offer greater usability of the individual sites.

Students proposed to focus on three main objectives in their design: use of local sustainable building materials, passive heating and cooling systems, adaptation to local topography and site constraints.

3.5.1.1 Flexibility and Growth

One of the main problems with the Corazon prototype and many affordable houses is their inflexibility and inability to grow. Instead, this house can grow and evolve. One of several possible paths to achieve the final phase is presented in Figure 3.92.

Prior to the construction of the building, grading, gabion retaining wall construction, drainage swales, and earth bag walls can be constructed by the community. This requires very little outside resources, because much of the materials comes from the site itself. Next, the building's slab on grade foundation system can be poured.

The first phase of the house is 29.75 m^2 and includes a kitchen, sleeping area, and bath, and the house can grow to include several bedrooms enclosing a courtyard (Figure 3.92). The construction consists of gabion units, earth walls, and lightweight framing. Depending on the location of these walls, either lightweight or heavy mass components would be used. A loft is above the kitchen/bathroom area and can be used for sleeping or storage. In the second phase additional sleeping pods that are approximately 2.44 m × 3.05 m are added as the family grows and has more resources (Figure 3.93). The sleeping pods use the gabion units for walls,

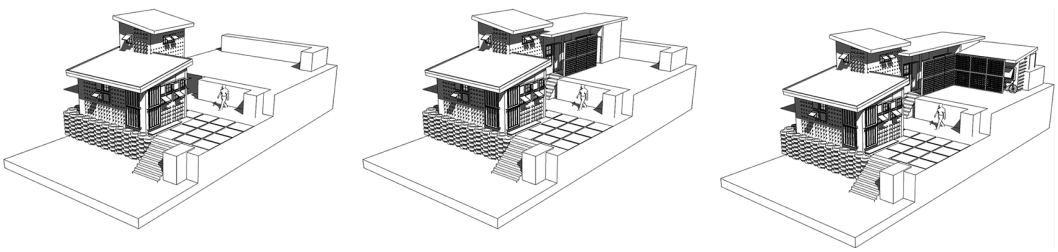


FIGURE 3.92 Possible growth in the Tijuana low-cost housing prototype.

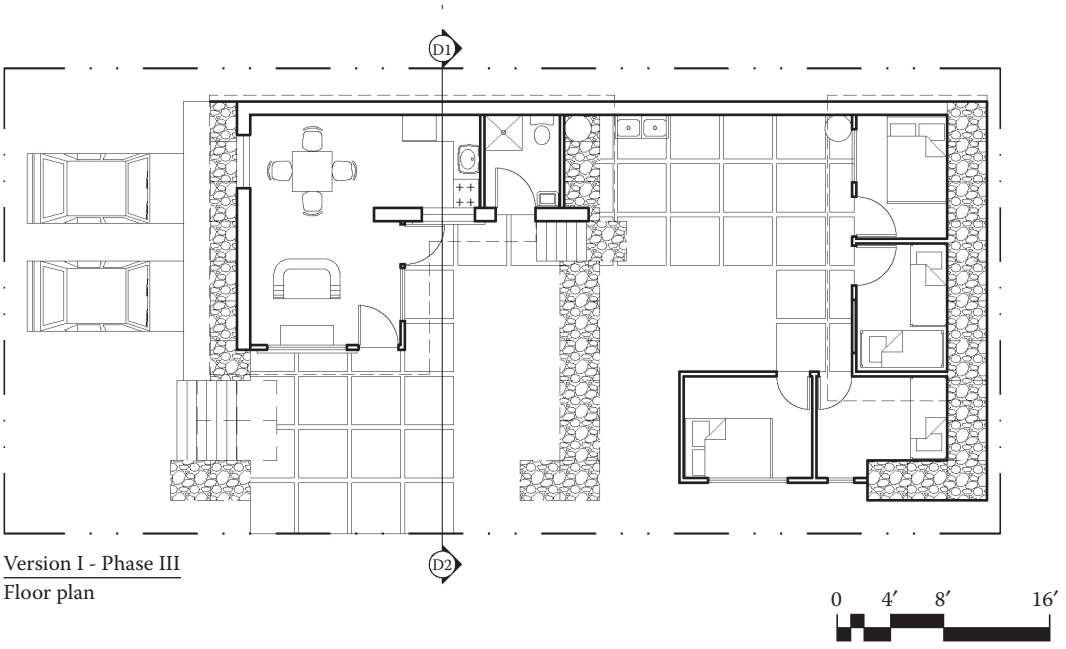


FIGURE 3.93 Tijuana low-cost house variant A.

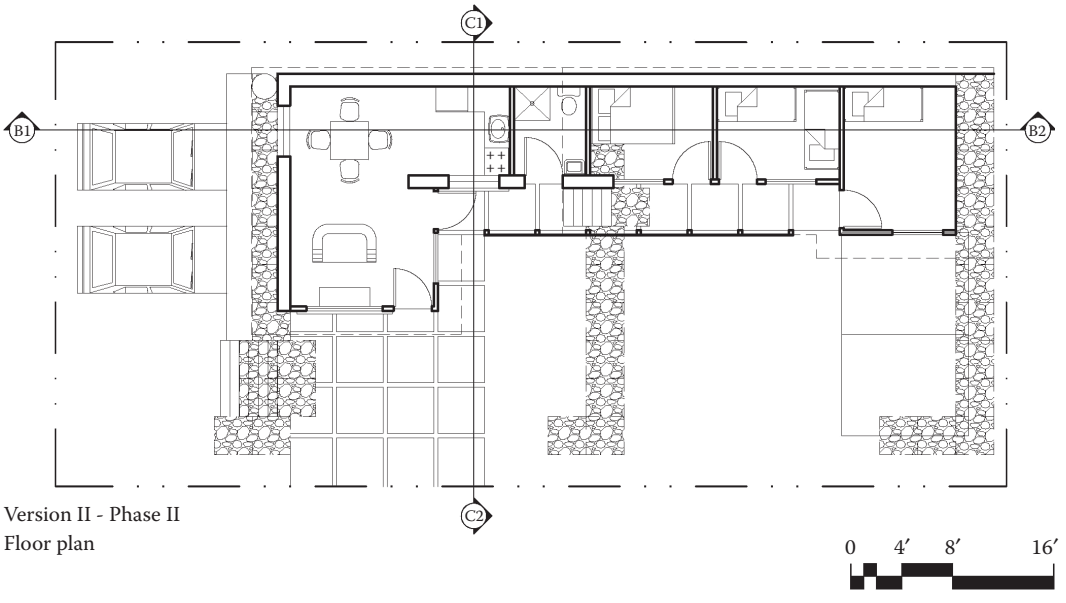


FIGURE 3.94 Tijuana low-cost house variant B.

earth wall, and wood framing. These sleeping pods can be arranged in two versions: either creating two "L" shaped buildings or creating one "U" shaped building (Figures 3.93 and 3.94). These configurations depend on the site, neighbor relations, and most importantly, input from the occupants. By scheduling the development in phases, the construction work can be done in a short amount of time, while construction costs are also minimized.

3.5.1.2 Site, Landscaping, and Green Roof

Corazon's home building program takes place in several neighborhoods or "colonias" in Tijuana. Most of the lots in these colonias are located in very steep slopes with poor soil and a plethora of cobblestone-sized rocks. The soil is currently excavated into terraces and left exposed, sometimes to heights exceeding 2 m and sometimes very close to the house or with the house precariously built above one of these terraces, in extremely dangerous conditions.

Storm water runoff is a significant challenge in the community, with drainage problems and mudslides, and should be addressed at the site scale. Rain catchment systems help to collect, store, and direct the water via gravity. However, runoff from adjacent properties must be addressed.

An "extensive" green roof has been incorporated into the design to assist in mitigation of rainfall runoff while providing improved heating and cooling performance and an increased roof life expectancy due to reduced UV exposure. An extensive green roof is proposed on the larger west-facing roof of our prototype in order to provide protection from the hot afternoon sun. On top of the wood decking we placed an impermeable layer of plastic as a moisture barrier. "Cal Earth" bags (rice sack material) are filled with a growth medium that is a mixture of native soil and vermiculite (to reduce weight) and are placed on the roof in rows perpendicular to the slope of the roof. These bags are designed to store earth and are very inexpensive, lightweight, easy to transport, and biodegradable to sunlight. They allow water to pass through them while containing the growth medium. These bags can be easily transported onto the roof as well as providing a structure around the soil while allowing the roots to establish themselves. Should one bag need to be replaced, it can be pulled out easily without having to replace the entire roof. When positioned on the roof the top side of the bag was cut open, and a variety of sedums and succulents native to Tijuana in addition to vegetables were planted. This allows for flexibility depending on the load that the roof can carry. In addition to the environmental benefits of green roofs, in this roof the soil is uninsulated and thermally coupled to the interior so that it can provide thermal mass as a heat sink in the summer, when the buildings could be night ventilated. Figure 3.95 shows the green roof as built while Figure 3.96 shows the green roof with alternative wall construction materials, which at the end were not used.

FIGURE 3.95 Green roof in the Tijuana house prototype.

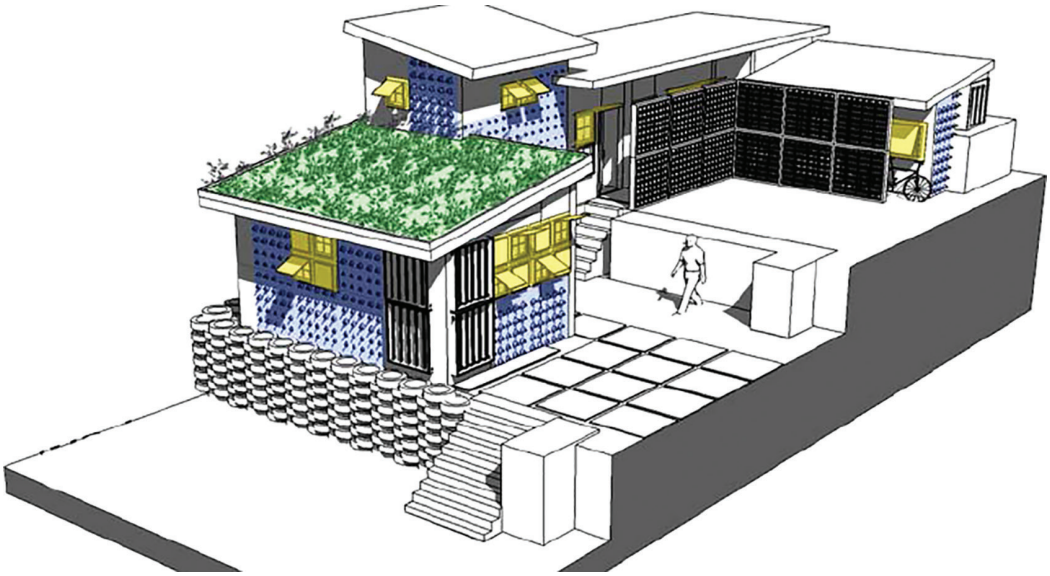


FIGURE 3.96 Green roof and alternative materials in the Tijuana house prototype.

Landscaping with native vegetation and food production would take place in the courtyards defined by the buildings. By incorporating the production of food into the community, a variety of positive effects can be realized. Fresh, nutrient-rich, local produce can be grown on-site to incorporate diet diversity. Compost bins could also be placed in this courtyard space. The act of growing food within the community increases food security, saves money, and increases community pride.

3.5.1.3 Local Materials and Papercrete Walls

In conditions such as Tijuana's it is important to use materials from the site. Since they own the property, they do not have to pay to buy or remove the materials; they are readily available as a result of the grading process; materials from the site contain less embodied energy than processed materials; and being from the site, these materials acknowledge traditional building forms. The soil generated from the grading process could be used in the walls, while rock also from the grading can be used to fill gabion units used for both walls and retaining walls. After several tests, walls were built with papercrete, a mixture of Portland cement, earth, and shredded waste newsprint. A tow mixer with 150-gal capacity was used to mix these and the papercrete pulp was poured in the walls (Figures 3.97 and 3.98). This material was easily cut with a chainsaw. Some blocks were also set with a papercrete mortar. The gabion units comprised of rocks placed into square wire "baskets" measuring approximately one cubic meter. These are then stacked and tied together to act as retaining walls. The interior of these can be plastered, much like the earth bag walls. Wood trusses to support the roof were constructed from wood pallets, and nails for $8 in materials per truss (Figure 3.99).

FIGURE 3.97 Interior view of Papercrete walls.

FIGURE 3.98 Exterior view of Papercrete walls.

FIGURE 3.99 Interior with wood pallet truss.

3.5.1.4 Adapting to Local Topography

The majority of the lots in the community are located in very steep slopes that would be considered unbuildable in many communities. The use of the gabion units provides a dual purpose: terracing of the site and wall structure that provides thermal mass. The retaining quality of the gabion units is adaptable to site-specific considerations. These retaining walls provide a usable space for the occupants and also help improve the general neighborhood conditions of soil loss, slides, and massive erosion. The structures are designed for modularity and future expansion. Site orientation will be dependent upon the lot location and the prototype was designed with this in mind; thus adaptability is inherent (Figure 3.100).

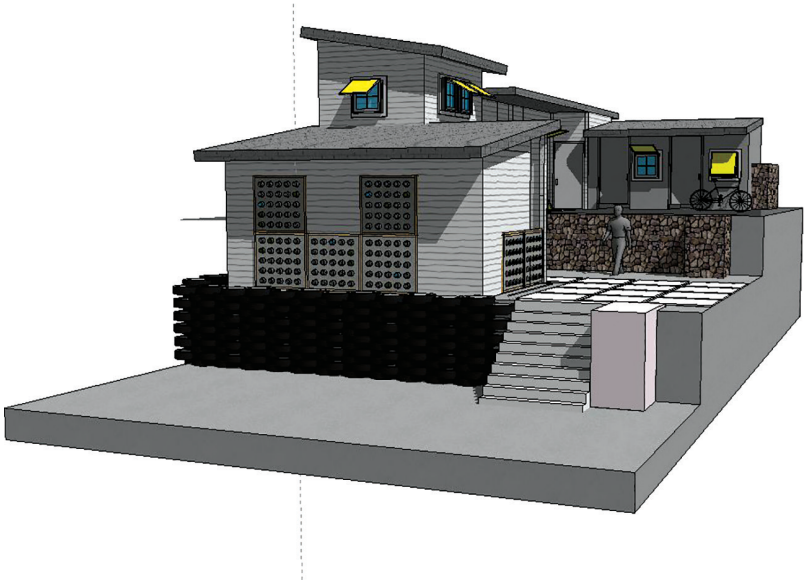


FIGURE 3.100 Initial proposal with tires and gabion walls to adapt to local topography.

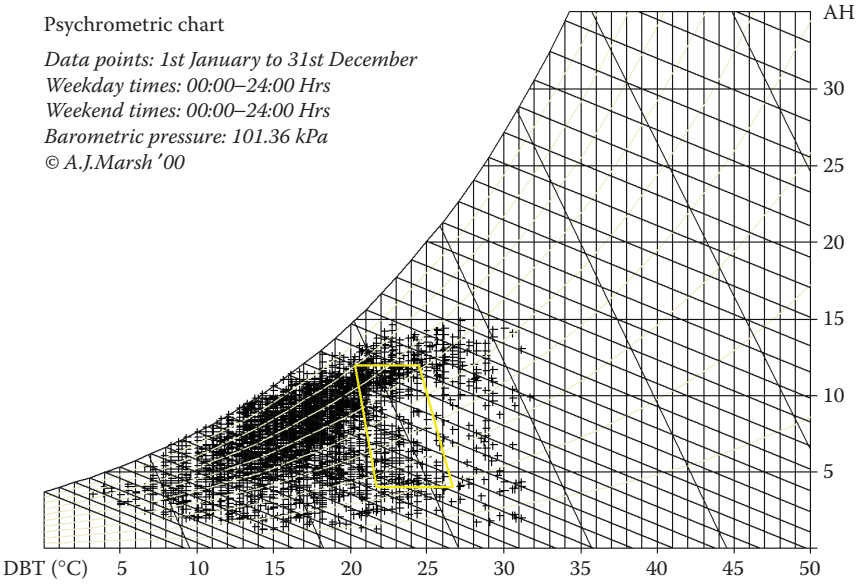


FIGURE 3.101 Psychrometric chart for San Diego just north of Tijuana.

3.5.1.5 Passive Heating and Cooling

As can be seen from the psychrometric chart (Figure 3.101), passive heating in the winter helps to achieve thermal comfort while ventilation, which can be either during the night or during the day, helps to achieve thermal comfort in the summer.

Materials with high thermal capacity are used as heat sinks in the winter and summer. Concrete floors and earth bag walls provide the mass needed for thermal storage. Several strategies to heat these materials in the winter were tested, including direct solar gain, solar air heaters integrated in the south walls, and hydronic systems with solar collectors to heat the water (Figure 3.102).

Operable windows are also placed along the southern and eastern façade, providing natural light, ventilation, and solar gain in the morning, and in the case of the southern elevation, during the whole day in the winter. Additional windows provide radiation during the early afternoon in the winter. Many of the windows are also placed near the ceiling to further improve natural ventilation and daylighting (Figure 3.103). Students further developed additional systems for shade and color using inexpensive canvas (Figure 3.104).

Thermal simulations were done with HEED. Twelve warm days in the summer and 12 cold days in the winter were analyzed. The indoor temperatures in the winter ranged from 10°C to 19°C while in the summer they ranged from 23°C to 28°C. These simulations only accounted for heating provided by direct passive solar gain through the windows and did not account for additional systems that could be implemented in the buildings, such as the hydronic heating system. Nevertheless, even though indoor temperatures in the winter night can be out of the comfort zone, they are much higher than the temperatures recorded in several existing houses in the winter of 2006 when we first visited their neighborhood.

Students also developed several active systems for the house including a low-cost solar hot water system for domestic and radiant heating, a solar air heater for the living room, and even a low-cost PV system to power lights and a music system (Hansanuwat, Lyles, West, and La Roche, 2007; Jeerage, La Roche,and Spiegelhalter, 2008; West and La Roche, 2008).

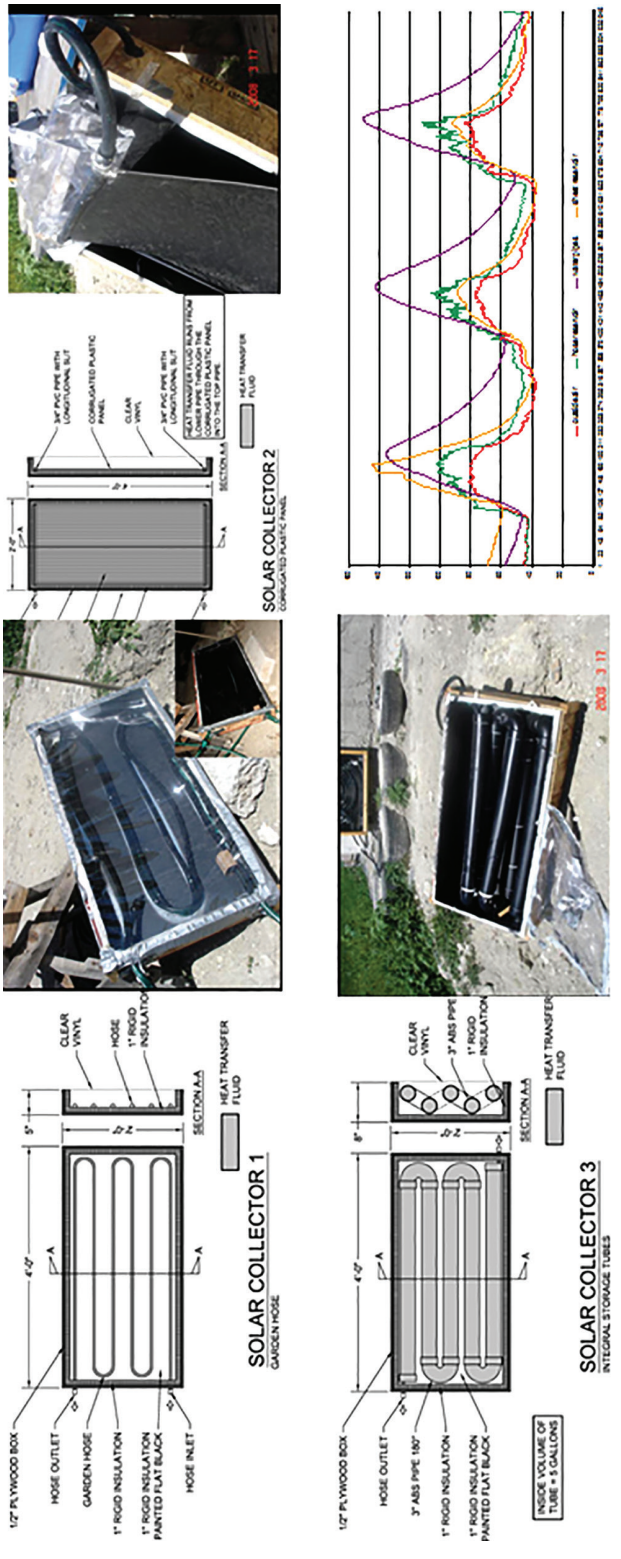


FIGURE 3.102 Students testing low-cost solar hot water systems for installation in the Tijuana house prototype.

FIGURE 3.103 South façade of the Tijuana house prototype built at the Lyle Center for Regenerative Studies.

3.5.2 Cerro Azul Community Center

Cal Poly Pomona also collaborated with Corazon in the design of a community center in Cerro Azul, close to Tecate, Mexico, just south of the border with the United States. The center, currently under construction, when finished will provide skills training workshops for adults, daycare facilities, meeting spaces for the community, and volunteer housing.

Corazon wanted to build the center in phases, so the students proposed a group of buildings that could be built independently by the community, volunteers, and students (Figure 3.105). Students in the architectural design studio designed the center with active participation of the Corazon (the NGO) and the community. They met with the community in Mexico, which shared with them their desires and aspirations for the center (Figure 3.106). Corazon staff participated in the studio reviews and provided input during the design process. All student projects proposed the use of local materials and passive low-tech strategies to achieve thermal comfort (Figures 3.107 and 3.108). A student project was selected for construction, and the project has also evolved as the buildings have been built and systems are refined and tested on site (Figure 3.109).

Later, in the elective course students focused on specific issues such as water, energy, waste, or materials, and designed solutions that were built and tested in class. Systems included rain water harvesting, low-cost solar hot water, solar cooker, evaporative cool towers, passive heating with direct gain, a solar attic, and even a rammed earth house. To study these issues, students used experimental research methods to study the impact of one or more identifiable variables on the phenomenon they were studying, which involved designing, building, and testing a real system and then analyzing the data.

Some of the systems such as the evaporative cool tower and the solar attic were further refined and integrated in the building to provide passive heating in the winter and passive cooling in the summer. Summers are very hot and dry with temperatures easily reaching 35°C during the day but going down to 15°C at night. Winters can be cool with temperatures between 3°C at night and 18°C

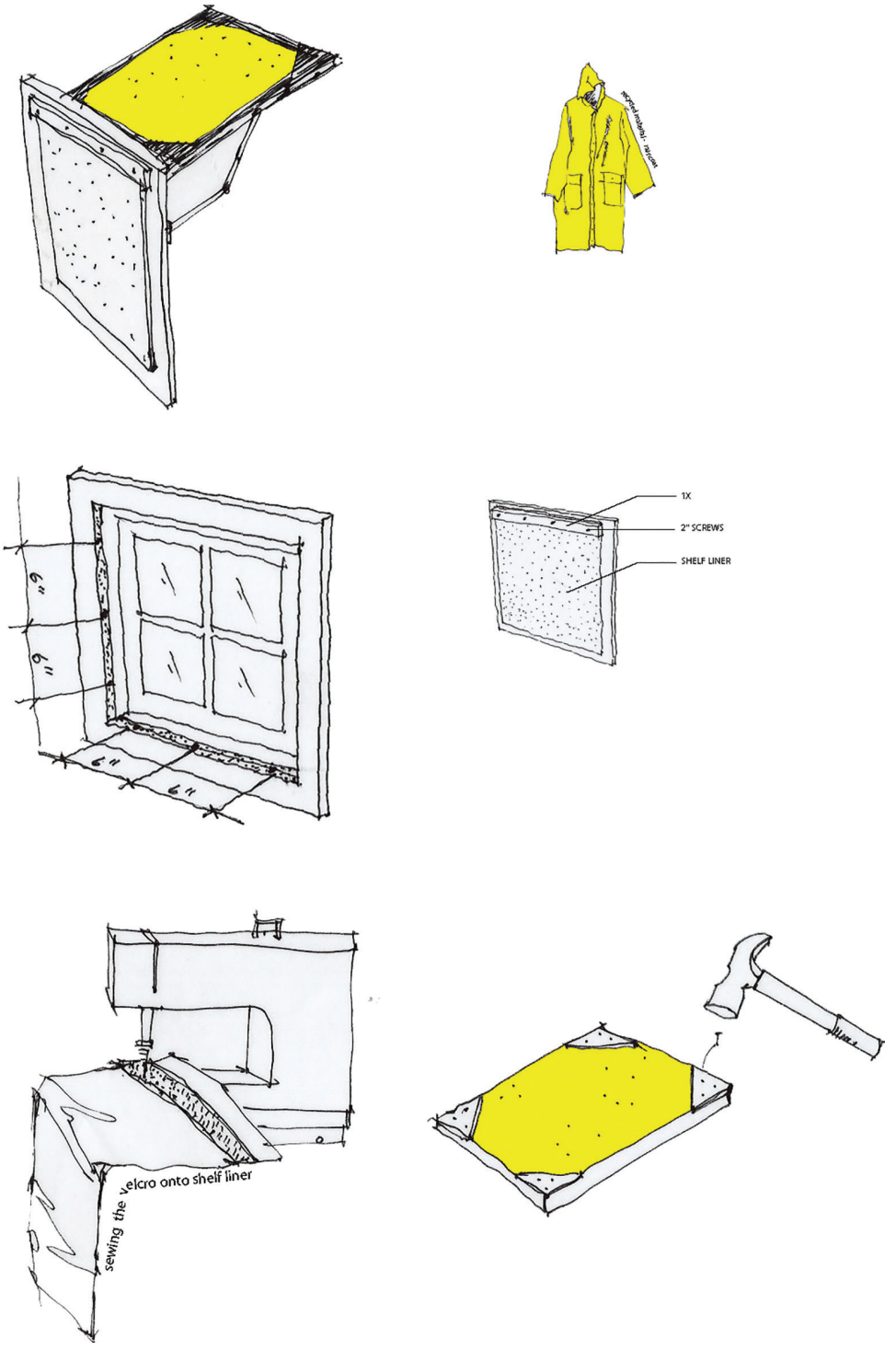


FIGURE 3.104 Low-cost shading systems developed by the students.

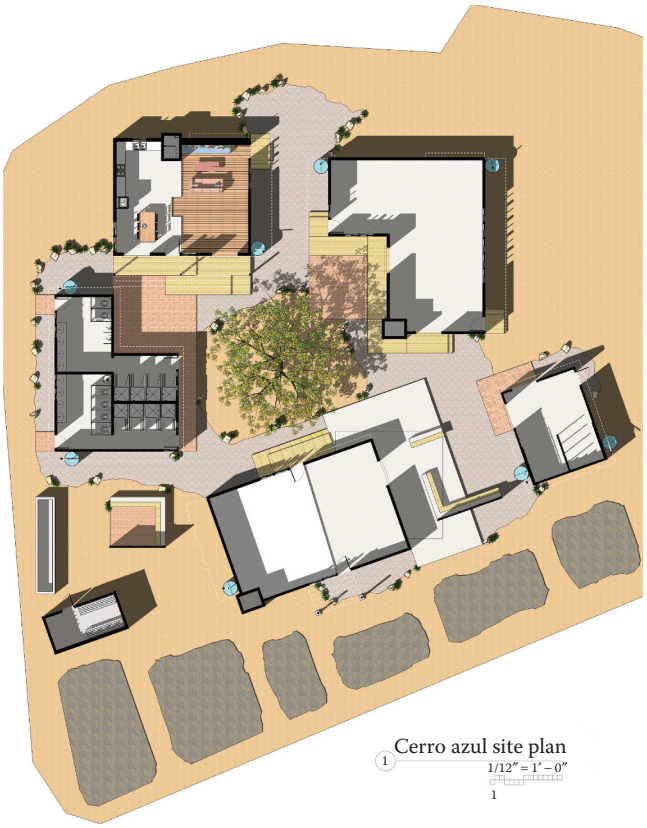


FIGURE 3.105 Cerro Azul Community Center site plan. (Courtesy of Cal Poly Pomona students Barbara Gonzalez and Hailey Peitzman.)

FIGURE 3.106 Cal Poly Pomona students with Cerro Azul community.

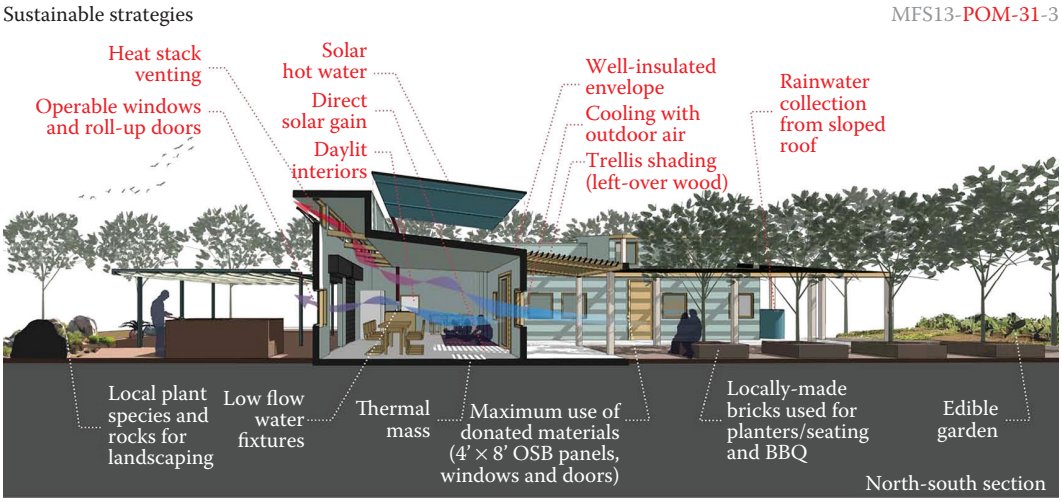


FIGURE 3.107 Community center proposal. (Courtesy of Cal Poly Pomona student Neila Naversen.)

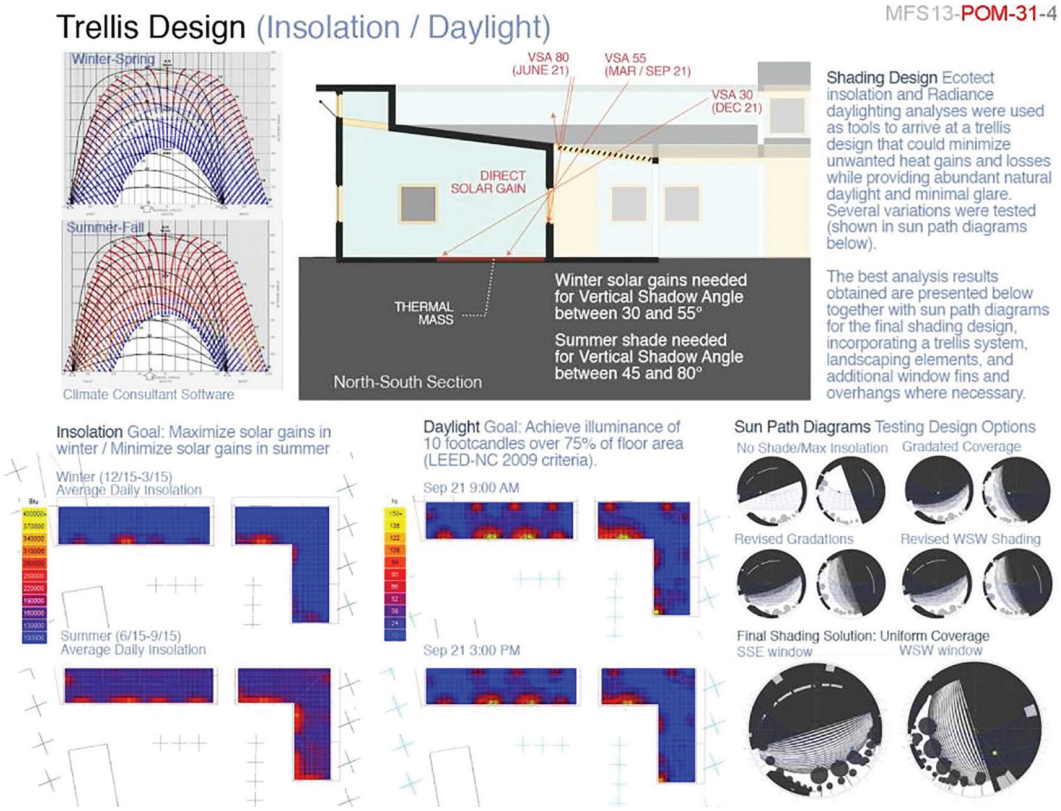


FIGURE 3.108 Shading design and study for community center proposal. (Courtesy of Cal Poly Pomona student Neila Naversen.)

FIGURE 3.109 Updated classroom design. (Courtesy of Arianne Ponce.)

during the day. Passive systems for the summer and the winter were designed and first built and tested at Cal Poly Pomona by a group of students. In the summer an evaporative cool tower provides cool air inside the building using showerheads. A prototype was built by students and tested at the Lyle Center (Figures 3.110 and 3.111). After it cools the space, it can exit through the solar attic or an open window (Figure 3.112). Several tests have been done with the cool tower at the Community Center which through evaporative cooling is able to cool air to 20.8°C with an outdoor temperature of 36.7°C and a RH of 24%.

FIGURE 3.110 Evaporative cool tower built at the Lyle Center. (Courtesy of Cal Poly Pomona students Tung Pham, Carl Reed, Mariko Hamagami, and Boshiang Lin.)

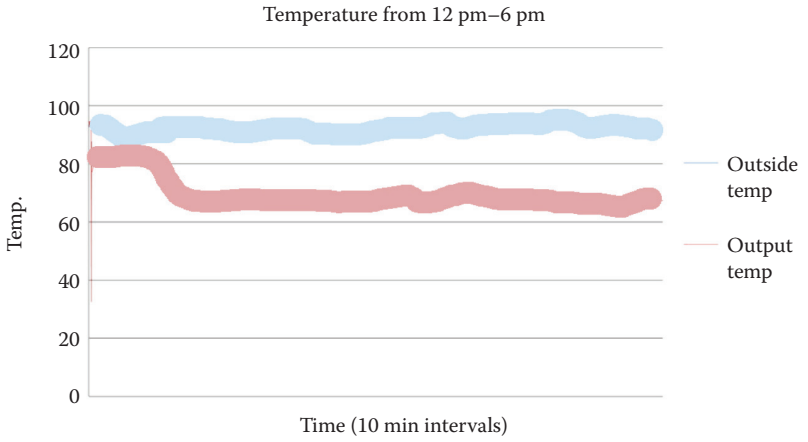


FIGURE 3.111 Measured temperature from the student-built evaporative cool tower built in Cerro Azul. (Courtesy of Cal Poly Pomona students Tung Pham, Carl Reed, Mariko Hamagami, and Boshiang Lin.)

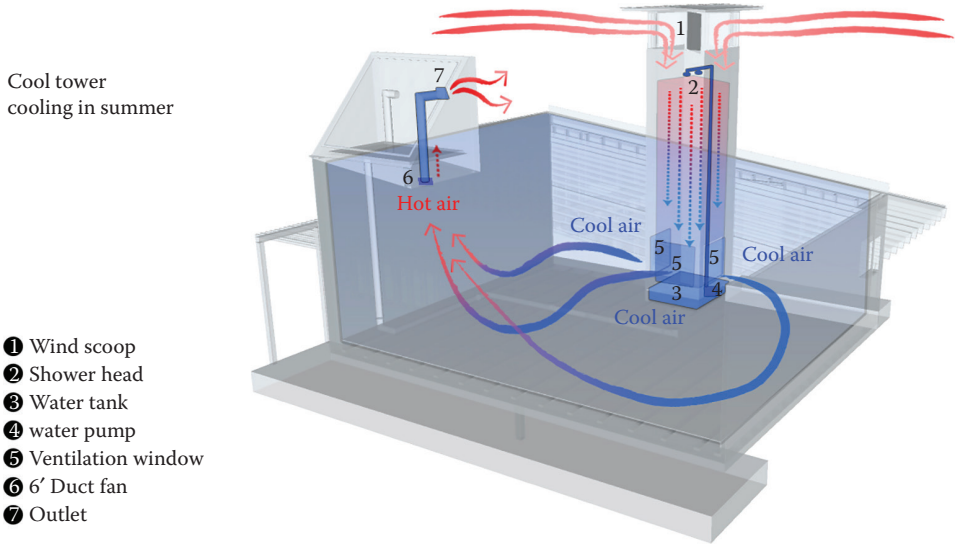


FIGURE 3.112 Summer cooling in one of the community center buildings. (Courtesy of Dongwoo Yeom.)

In the winter a solar attic in the roof heats the air while a small fan pumps it down under the raised floor, warming the indoor space with warm air from the underfloor air distribution system. Tests in the building in Mexico measured air coming from below at 33°C. This concept was tested by several students and in different configurations (Figure 3.113). Several versions of the system were also developed. The final one is shown in Figure 3.114. Thermal mass in the attic stores heat to provide some nighttime use. There are a total of five buildings and one of them is finished with another under construction (Figures 3.115 through 3.117).

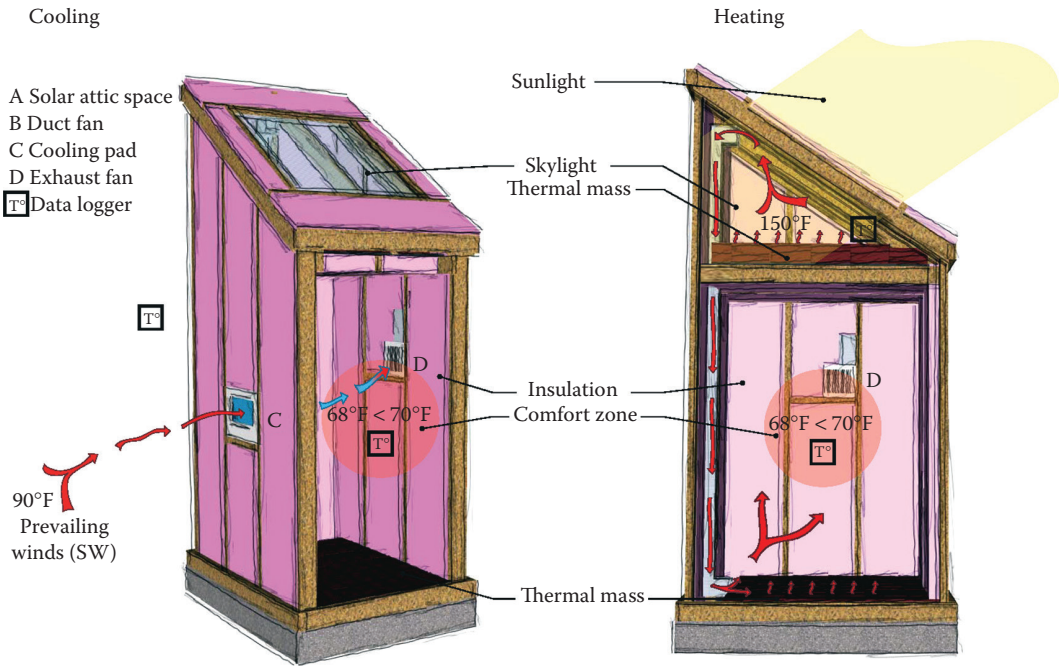


FIGURE 3.113 Solar attic test. (Courtesy of Cal Poly Pomona student Barbara Gonzalez.)

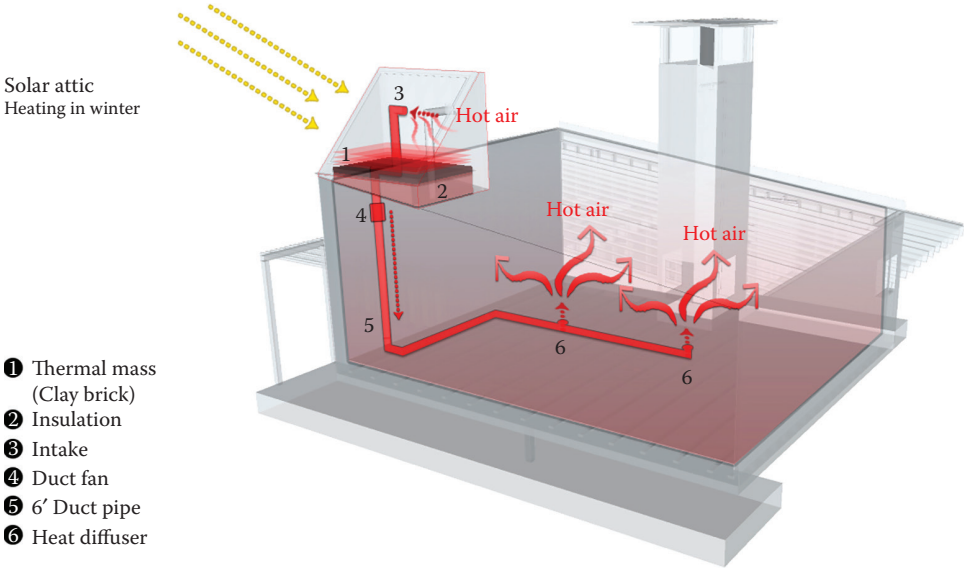


FIGURE 3.114 Winter heating design. (Courtesy of Dongwoo Yeom.)

FIGURE 3.115 Kitchen-office-meeting space of Cerro Azul Community Center Building under construction.

The center will be opening in spring, 2017 and will provide skill-training workshops for adults, daycare facilities, meeting spaces for the community, and volunteer housing. Training in the construction of these passive systems for on-site adaptation for existing dwellings (currently none have heating or cooling) will provide a source of income while improving living conditions: true social, economic, and environmental sustainability. Similar projects provide students with the opportunity to do good while learning from practice (Figures 3.118 and 3.119). Furthermore, this is an opportunity to implement strategies that contribute to a contemporary vernacular in communities in which sustainability is not a matter of saving energy, it is a matter of health.

Several common threads are clear in these projects. The first is that these communities cannot afford to buy mechanical heating and cooling systems, nor can they afford the energy needed to operate them. Passive cooling and heating are then required for both health and comfort; there is no other option.

Technology has to be appropriate for the cultural and economic conditions of the community, and the owners must be able to afford their buildings, while being proud of them. The homes in the communities in Mexico are designed to provide flexibility, potential to grow, and adaptability to steep topography. Owners can and will modify and adapt them to the requirements of their families and their site.

FIGURE 3.116 View of the office/kitchen/meeting space with solar attic in the foreground and cool tower in the background.

FIGURE 3.117 View of the centre with bathrooms to the left, office/kitchen/meeting at centre and classroom to the right.

FIGURE 3.118 Mexican community working with Corazon volunteers from California.

FIGURE 3.119 Aerial view of the community center under construction.

A model that combines design with research in the development of alternate sustainable systems in a combination of design studios and research seminars provided opportunities to better develop projects and systems at multiple scales.

Performance-based design was integrated in the studio design process. In the seminars it was based on the experimental research model.

Time is always an issue, especially when building, and even more when designing and building in another country.

4 Carbon-Neutral Architectural Design in Practice

While the previous chapter explained some principles and strategies to achieve carbon neutrality with examples from student projects, this chapter is about carbon neutrality in practice and is divided in three sections with examples from my professional practice. The first section is also about architecture with social responsibility using an author's project; the next section discusses integrated strategies to achieve carbon neutrality using another project as a case study. Finally, the third section discusses the design process and the digital and analog tools that can be used to achieve high performing buildings.

4.1 SOCIAL SUSTAINABILITY: NUEVA DEMOCRACIA

Sustainability is also an instrument for social justice. It is not possible to achieve carbon neutrality without improving the quality of life of those that have less. The world's most disadvantaged people suffer the most from environmental degradation, and in many cases, a minority is allowed to have more at the expense of a majority that has less.

In most developing countries, urban growth in the last 60 years has been defined by the construction of cities, economically and socially divided in two different urban groups, the formal and the informal, which can be up to 60% of a city (Todaro, 1997). In developed countries there is no informal sector, but many cities are still divided, sometimes autosegregated, with widely differing access to basic needs, amenities, and services.

Climate change is also affecting development, which in the world's poorest countries could be halted or even reversed by mid-century unless bold steps are taken now to reduce climate change, prevent further environmental damage, and reduce deep inequalities within and among nations (UNDP Human Development Report 2011, http://hdr.undp.org/en/reports/global/hdr2011/). Climate change is augmenting the effects of climate-related disasters that are now more severe and frequent. Earthquakes and tsunamis continue to affect ever more populated areas with many substandard buildings affecting more than 200 million people in the last 10 years.

4.1.1 Urbanization in Venezuela

Venezuela's urban population now accounts for more than 90% of its total population and of these more than 60% live in precarious human settlements. Venezuela's case is similar to that of many developing countries, in which migrations from the countryside generated explosive and unmanageable city growth, which could not be managed by the state. However, after the 1990s urban growth in Venezuela is not the product of rural migrations; it is the product of its own natural growth. In Maracaibo informal housing or "barrios" account for more than two-thirds of the city's population (Echeverría, 1995). This housing is generally self-built or built by local men without construction documents, not following any city codes and generally lacking sanitary services.

4.1.1.1 Urban Development with Community Participation: Nueva Democracia

Without the ability to find appropriate dwellings in the formal sector, most of the population that does not have access to housing opts for the informal sector, generally by moving into unbuilt lots and building precarious housing in less than 24 hours. These houses are generally built with discarded construction materials such as tin sheets and bricks organized in very inefficient urban

design with very low density, generating problems for municipalities, which are not able to serve them appropriately. Sometimes the settlements are dismantled, but most of the time, the houses consolidate and receive access to public services, but the poorly laid-out plan makes it very expensive to access these services.

In January 25, 1994 a group of 1069 families violently occupied a vacant lot in northern Maracaibo. However, the regional government negotiated with the squatters and convinced them to leave peacefully if they would provide them with a strategy to legally occupy the lot. The community and the government reached out to the department of architecture to design a project in this site, while the community organized and bought the property from the government. "Nueva Democracia," which means New Democracy was developed in 1996 as a collaboration between the Social Development Institute (IDES) of the state government, the community, and the School of Architecture of the University of Zulia. The members of the community were mostly young (between 25 and 40 years) and with an average monthly family income between $75 and $350. They were not the poorest of the poor in Venezuela, but are in the bottom half.

Three project levels were established: the urban, the intermediate or condominium, and the dwelling, promoting a more cohesive group and social organization at these three levels: represented the community group, the neighborhood organizations around 12–30 families and the basic cell of the civil society: the family. Each architectural level was specifically related to an organizational level.

4.1.1.2 Urban Design

The project was designed to be habitable with minimum investment by the government and the occupants, allowing more homes to be built for more families. All urban spaces could be developed with community participation and have evolved in this manner. Nueva Democracia is not a strategy to stop urban growth; it is a strategy to improve the quality of life in disadvantaged communities with community participation, growth, and flexibility. It is difficult for architects to modify the macro factors that affect urban growth, but we are able to improve the quality of life in impoverished urban areas.

The following criteria summarize the basic principles that sustain the urban design:

- Rational occupation and use of the space to optimize infrastructure reducing urbanism costs (Figure 4.1).
- Minimization of public and semipublic areas, which are difficult to maintain and control. This reduces unattended and dangerous no-man's-lands existing in many affordable housing projects.
- Increase in the physical controls of the community spaces through appropriate definition of properties, use of space, and transitions.
- Strengthening community integration through design, so that they support the positive evolution of the community expressed in the housing and urbanism.

4.1.1.3 The Condominium

A very important design consideration, at all levels, was to promote strong neighborhood relations to strengthen the community. Housing was organized around the community spaces (condominiums) for dwellers to maintain perceived and control over these semiprivate spaces.

The condominiums provide a different organizational model that reinforces the ownership sense of families around a territory that is their own and recognizable. The condominiums were proposed to increase private and semiprivate spaces over public and semipublic spaces, establishing the responsibilities of the communities around them, ensuring the responsibilities for the conservation and improvement of these spaces (Figures 4.2 and 4.3) (Echeverría et al. 1995). These spaces are owned by the families surrounding them, and maintenance of these spaces is their responsibility.

FIGURE 4.1 The urban design, with condominium spaces surrounded by homes.

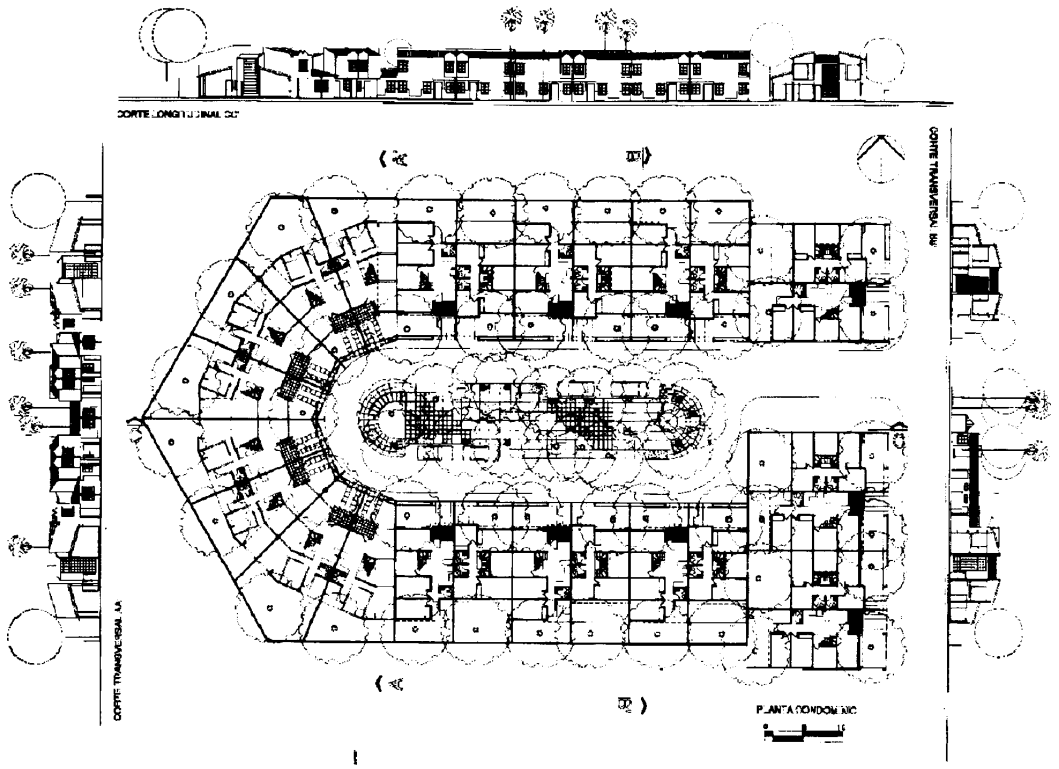


FIGURE 4.2 The condominium in Nueva Democracia. The central area is owned by the community around it.

FIGURE 4.3 Condominium homes typically grow quickly. (Courtesy Daniel Velazco)

Each of these condominiums has an area for community use, with game areas for children and youth, child care centers, and possibilities for small businesses. Different strategies were developed for growth including one that has green roofs (Figure 4.4). The homes around them are spatially integrated with the condominium space and have grown quickly (Figure 4.5).

4.1.1.4 The Dwellings

The houses are designed to grow from a very small 30 m^2 unit with a multiple living-sleep space with bath and laundry to a house with five bedrooms, living room, dining room, kitchen, laundry room, backyard, front yard and courtyard, porch, and a place to park the car. The house is a succession of geometrical elements around an internal courtyard, from an "I" to an "L" to a "C," providing light and ventilation inside (Figure 4.6). By providing an opportunity to grow, the family can expand the house, according to their income. First costs are slightly higher initial costs but are quickly compensated with additional flexibility in the house.

The design includes references to the traditional houses of the late nineteenth century in Maracaibo, which also enhanced community relations and public spaces, with internal courtyards and a permeable urban façade, values that have been lost in many contemporary homes (Figures 4.7 and 4.8).

Flexibility is a key principle in the design of the Nueva Democracia homes. The occupants have been involved in the transformation and growth of the house, without the usual risks of

FIGURE 4.4 Proposed growth strategy with green roofs. (Courtesy Daniel Velazco)

FIGURE 4.5 Image of one of the condominiums in its early years around 1998.

unplanned alteration. The design is such that the owners can expand and modify their homes, as they always do, in their quest to individualize and adapt them to their particular needs in a way that the original design is barely recognizable, and many houses have grown incredibly in a very short time; some are already two floors high in their final growth stage (Figure 4.9). The design allows multiple alternatives at different stages but all of them are much better than the rest of the informal communities around them that did not benefit with this process (Figure 4.10).

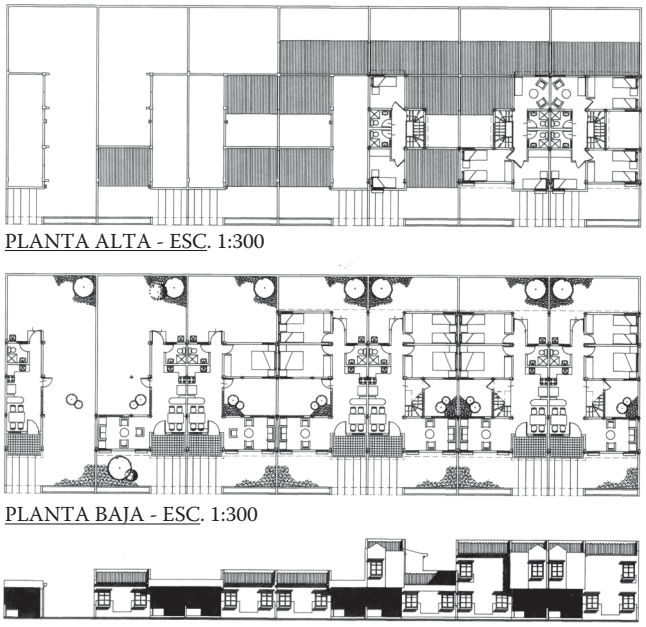


FIGURE 4.6 Growth in Nueva Democracia home.

FIGURE 4.7 Interior view of a house with courtyard around 2000.

Subsequent visits and interviews with some of the residents indicate that the owners are happy and satisfied with the project, the communities in the condominiums are organized, and the owners are improving the quality of the spaces they own and control. December 2000 was the first Christmas in which most of the condominiums were occupied, and a competition was organized to see which condominium had the nicest Christmas decorations.

FIGURE 4.8 Interior view of a house with courtyard around 2000.

FIGURE 4.9 Exterior view of some of the houses around 1998.

FIGURE 4.10 Neighboring community with informal housing.

4.2 CARBON NEUTRALITY: TENERIFE

The project "To Inhabit de Device" designed by P. La Roche, F Mustieles and I. Oteiza was awarded one of 25 prizes in the international competition "25 Bioclimatical Houses for Tenerife" organized by the Colegio de Arquitectos de Canarias and sponsored by the International Union of Architects in 1995. The homes were built in phases and our project was completed around 2010. The 25 dwellings, together with a visitor's center, incorporate concepts that could later be implemented in other projects.

In 1995, for the competition, we organized our strategies to achieve a sustainable building in three main groups: energy and thermal comfort, materials and construction processes, and water and environment.

The main goals in each area were:

1. *Energy and Comfort*
   a. Reduce consumption of nonrenewable energy
   b. Reduce CO_2 emissions to the atmosphere
   c. Provide thermal comfort only with passive means and without any mechanical heating and cooling
   d. Reduce the emission of fluorocarbons to the atmosphere by 80%
   e. Provide 50% of the energy needed from renewable sources
2. *Materials and Construction Processes*
   a. Use recyclable or recycled materials
   b. Use local materials and technology
   c. Rationalization of the construction system to reduce construction waste
3. *Water Conservation and Environment*
   a. Use a waste classification system to facilitate recycling
   b. Reduce water consumption by 40% and use gray water for irrigation

4.2.1 The Project

The climate in the Canary Islands is very mild. The island enjoys a warm climate year-round with an average of 18°C–24°C in the winter and 24°C–28°C in the summer. Solar radiation is high and the ocean and trade winds regulate temperature. Humidity is higher on the north and northeast of the island, while the south where this project is located is very sunny and windy. The marine air contributes to extreme heat being rare and frost impossible at sea level.

There is no urban context to reference so the design references are cardinal and geographical. The building is oriented to collect solar energy and wind: fire, water, and air under one roof. The facade is mostly opaque to the north, and transparent to the south with operable shading. The north wall symbolically also protects from the Teide volcano while the best view of the Atlantic Ocean is toward the south (Figures 4.11 through 4.13).

One of our main design goals was the integration of bioclimatic and architectural concepts in a "livable device," combining technology and architecture to make the device part of man's space. We did not want our project to become a collection of strategies and materials added onto each other. We wanted to integrate these systems and wanted the dweller to feel that he was an important part of them. The inhabited triangular wind scoop is oriented to the northeast (Figure 4.14), capturing cool ocean breezes and moving them through the house (Figure 4.15). The second-floor living room is actually located directly below the wind scoop (Figure 4.16).

The building orientation responds to the sun and the wind. The main axis of the top floor is oriented east-west so as to maximize southern exposure. The south floor is rotated 45° to this axis, and connected to the wind scoop above, which captures the wind from the northeast (Figures 4.17 and 4.18). Window slits in this wall are shaded from the sun by its thickness and permit cross-ventilation in the summer, when they are open.

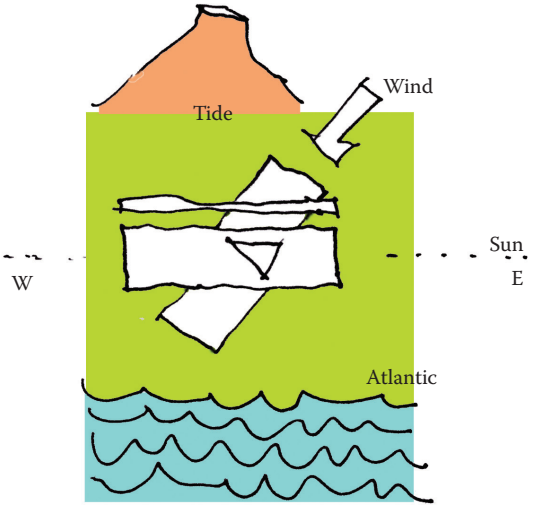


FIGURE 4.11 Strategies that affect the design concept.

FIGURE 4.12 Transparent façade to the south.

Climate analysis was the first step to reduce building loads using Fanger's comfort equations and Givoni's bioclimatical chart. At the time, in 1995, we did not have weather files with hourly data available so we did this analysis with monthly average maximum and minimum data. The data were compared with the strategies needed to achieve thermal comfort. Two conditions were typified: "winter" and "summer," with a day and a night condition for each one. A flexible space was designed that could adapt to outdoor conditions and be flexible in the management of the sun and the wind linked to daily and seasonal rhythms.

FIGURE 4.13 Opaque façade to the north.

FIGURE 4.14 View of the home with the wind scoop.

The building was oriented to capture the winter sun and the summer breezes while thermal mass is a heat sink for both summer and winter. Insulation reduces solar gains in the summer and heat losses in the winter. Direct solar gain provides heat in the winter while ventilation provides cooling in the summer, and sliding doors can block gains when required (Figures 4.19, 4.20 and 4.21). The north wall also shades summer sun and blocks the cold winter winds from the northeast.

These passive solar design strategies eliminated the need for a mechanical heating and cooling system. Energy modeling software (CODYBA) was used to determine thermal comfort. Predicted comfort was about 90% during the winter and 85% during the summer (Figures 4.22 and 4.23). Fall and spring should be more comfortable.

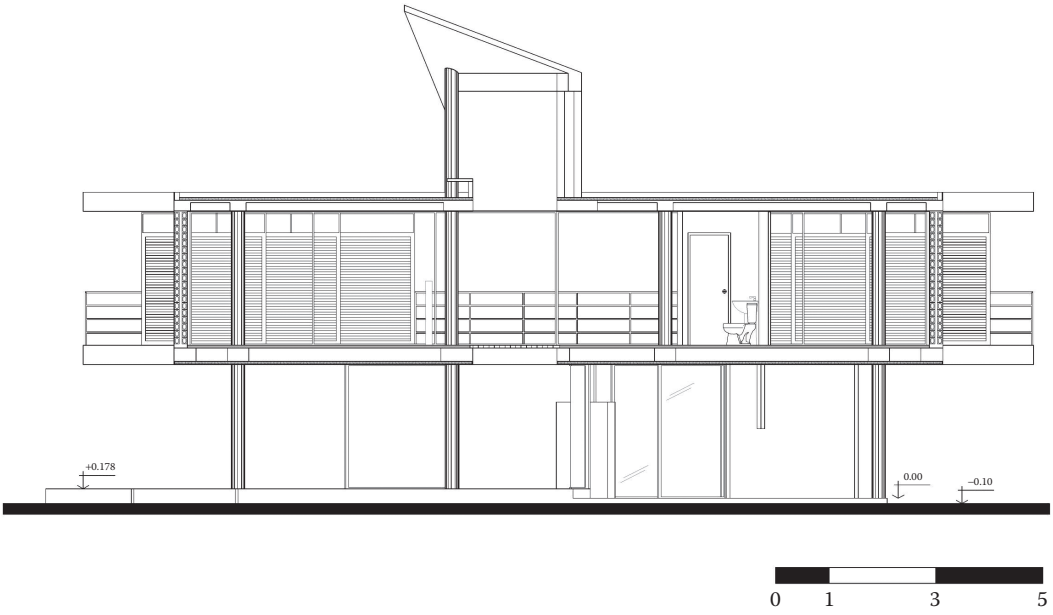


FIGURE 4.15 Section through the wind scoop.

FIGURE 4.16 Second-floor living room below the wind scoop.

Operable windows provide daytime comfort ventilation or nocturnal ventilative cooling, in which case nighttime air movement lowers the temperature of the internal surfaces of the floors and walls. The windows can be closed during very warm days, when it is necessary for the mass to keep the spaces cool, or can stay open for breezes on cooler summer days. All spaces can be cross-ventilated and the wind scoop provides additional breezes to the core of the building, through óthe second

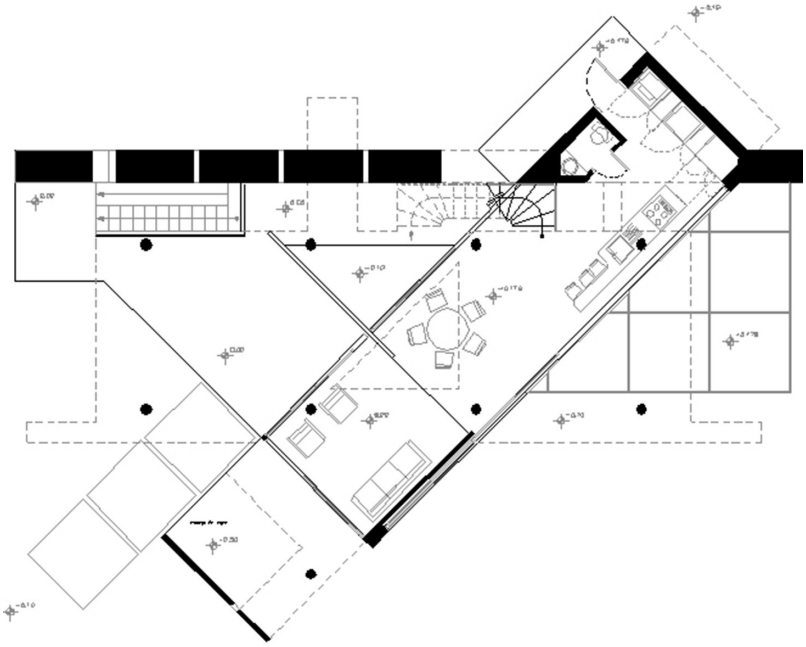


FIGURE 4.17 Ground floor.

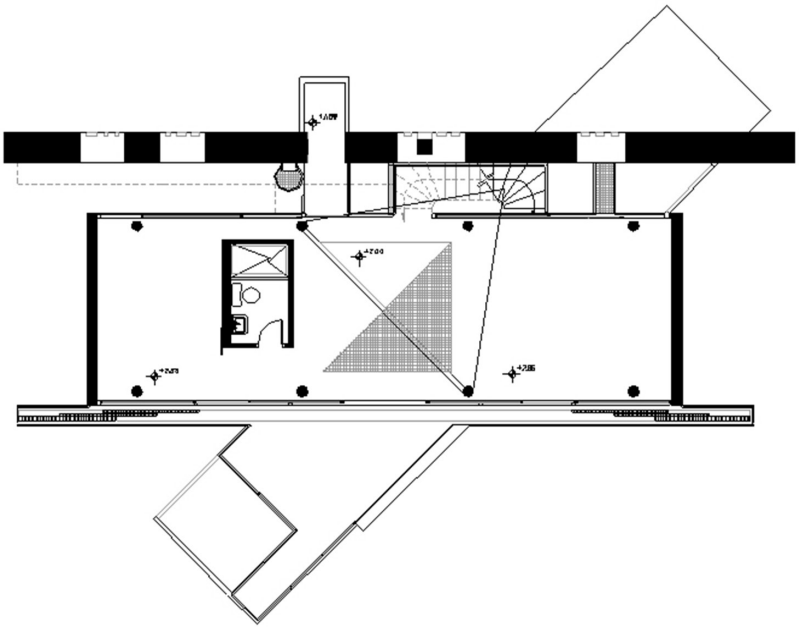


FIGURE 4.18 Second floor.

floor, down to the first floor. The house is connected to the grid and all of the energy is renewable, provided by Instituto Tecnológico y de Energias Renovables (ITER).

Daylight is provided through the windows and a light shaft between the north wall and the rooms.

A hot water system with collectors is located at the top of the north wall with a storage tank inside. The slope at the top of the wall is equal to the latitude. The dishwasher and washing machine are high

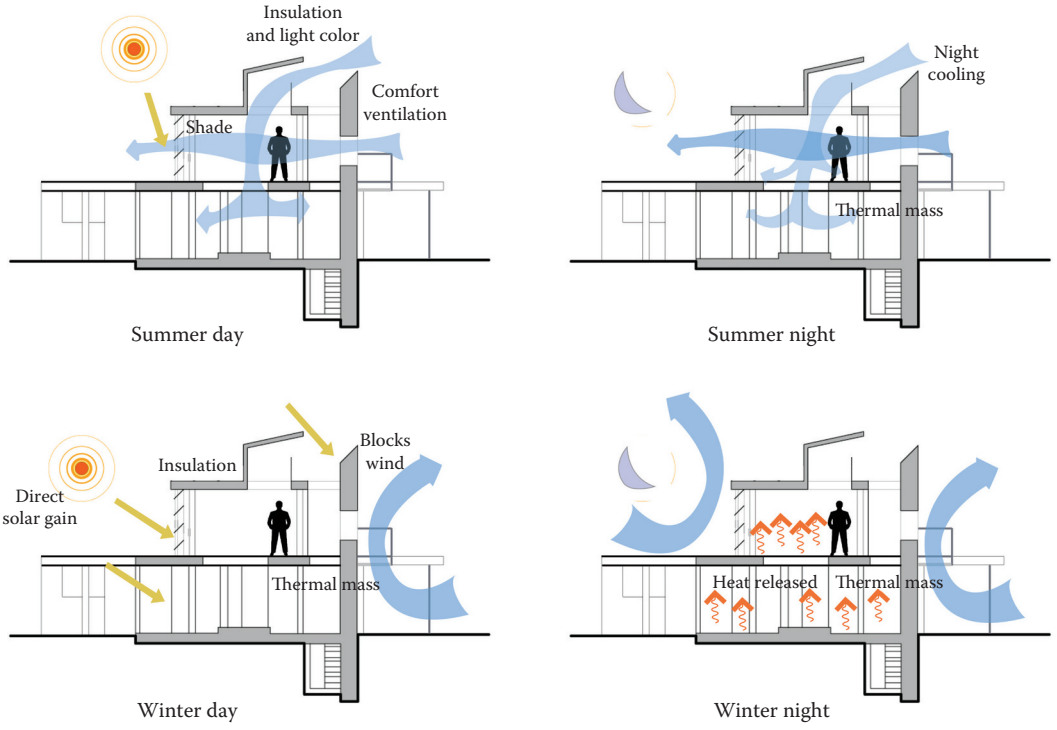


FIGURE 4.19 Summer and winter passive strategies.

FIGURE 4.20 South façade with sliding louvered doors.

FIGURE 4.21 Sliding louvered doors can control solar radiation.

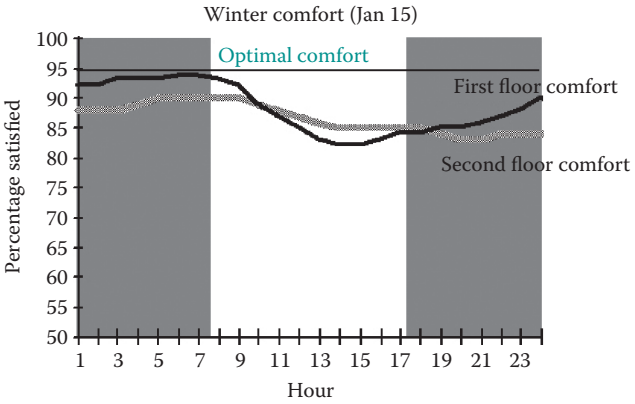


FIGURE 4.22 Winter comfort simulation.

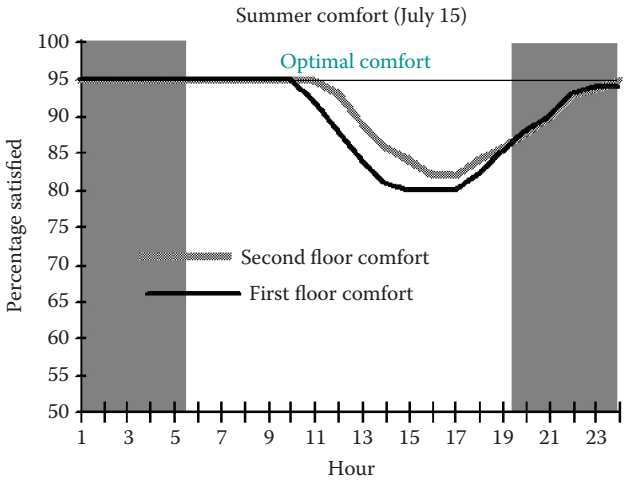


FIGURE 4.23 Summer comfort simulation.

FIGURE 4.24 Minimal site disturbance.

efficiency. All of the water coming from the dwellings and the office building is taken to a treatment plant and then used for irrigation. An automatic irrigation system uses little water for the native vegetation. Water fixtures are high efficiency. The toilet is double flush (6 L) the showerhead is low flow under 2 gpm, and the faucet also has a low-flow aerator under 1 gpm. There is no bathtub, only a shower.

Site disturbance was minimal and special care was taken to adjust to the topography so as to not modify the landscape (Figure 4.24). The overlapping of the building elements creates some exterior shade. Volcanic stone is used for hardscaping and is permeable to water.

The home is 120 m^2, which is smaller than the average Spanish home, and most of the construction materials are from the island. All materials were selected to withstand the harsh marine environment. Concrete bricks with volcanic rock aggregate were used for the walls and roof. This volcanic rock was used in the north wall and for the landscaping and paving outside. Forest Stewardship Council (FSC) European hardwood was used for some exterior pavements in about 15 m^2. The concrete with volcanic aggregate is better suited for the sea environment, readily available and common in the island while also being thermal mass. The structural system is rationalized following a module that allowed the use of prefabricated components made in Tenerife (Figure 4.25).

This house was designed many years before any major sustainable rating system was implemented in the United States, and we achieved most of our sustainable design goals. Many building energy codes do not sufficiently consider the benefits of passive heating and cooling. These codes typically emphasize insulation, and sometimes airtightness, to make the envelope more efficient, so that it helps to reduce heating and cooling loads. These codes usually do not assume that it is possible to design a totally passively heated and cooled building, even though it is possible in many climates, where passive solar designs can achieve thermal comfort with little energy use, eliminating CO_2 emissions. ITER currently rents the home, as the other 24, for short stays, after which the occupants fill a survey. Survey results have been mostly positive with the main complaint being the noise produced by the wind moving inside the house.

FIGURE 4.25 Local materials including volcanic rock are used for construction.

4.3 EXPLORING NEW DIRECTIONS

This section briefly discusses three ideas that explore current issues directly or indirectly related with a low-carbon world: inclusion, self-sufficiency, and the generation of clean energy and waste. Even though these ideas are only partially developed and are not intended to be seen as the "best" solution for each specific problem, they provide insights into apparently unrelated but in reality interconnected issues.

4.3.1 Inclusion

The quality of buildings and spaces has a strong influence on the quality of people's lives, and poor and disadvantaged people are far more likely to live in poor quality environments (*Inclusion by Design*, 2008). Social sustainability is also about inclusion and providing quality environments for all. Our Wired to Enable Home or W2E Home, developed with Maria La Roche and Arianne Ponce, submitted to the Autism Speaks "House to Home" competition, explored options for adults with autism supported by sustainable principles. Our concept was about production and connection, aided by communication and technology, both implemented to integrate adults with autism to the community. These concepts would be housed in a familiar enclosure, the home, probably the most familiar element to all adults with autism and one in which everybody feels, or should feel, safe and in comfort. This home environment would also be used for the production of goods and services and to connect with the community, probably through a small retail space. There would be areas for the occupants to live and feel at peace, but there would also be options to challenge the occupants and push them out of their comfort zone if needed, integrating them with the community. This would be a home about erasing barriers.

The W2E home could be implemented in locations with different densities (Figure 4.26); however, the higher densities of cities provide more access to urban amenities, more work options, and more opportunities to connect, such as libraries, public swimming pools, movie theaters, and parks. The home could be a single building or a group of buildings in one lot, or even a group of buildings close to each other, in separate lots. In locations with medium to high densities the building could be designed to feel as if it actually consisted of separate homes, maybe even three or four town houses located side by side, responding to, and engaging with the city.

The buildings would also incorporate many green features, including passive strategies, and incorporating daylight and views with all their benefits, increasing the connection between the

FIGURE 4.26 Layout options for different densities.

occupants and the environment around it. Equatorial-facing open spaces would provide opportunities for recreation and urban farming in cooler latitudes.

Themes and clusters would be the basic building blocks of the system. Themes help to organize the modes of production and connection areas in the home, providing options to develop theme-specific activities in addition to the general support spaces. The clusters are groups of spaces and activities that support the themes. All homes would have clusters that are part of the production and connection processes, but their content would change according to the theme. For example, all homes will have a production area, but these will be completely different depending on their use. Many themes could be developed and combined in one home or even shared by different W2E Homes. The themes dictate the types of productive and community activities and spaces. In a media theme the production area is digital and the space requirements to achieve the requirements are flexible, probably including a wired space, Internet connection, computers, and WiFi. The interaction area could include digital activities, and maybe even a small space to project movies and a coffee place. Building residents would interact with a virtual community around the world. In a food theme, food is also part of the productive activity and an instrument to facilitate community integration. Most autistic adults have some food preparation experience from the school and the home, so this is an area that can be further developed. In addition to food, retail is used as an instrument to help connect the occupants with the community. The production area includes planting, tending, and harvesting of the food, and an area for food processing such as jam production. The interaction area includes areas for cooking, serving, and eating (Figure 4.27). Food delivery is also an option to increase interaction with the community. Food flows respond to functional and material

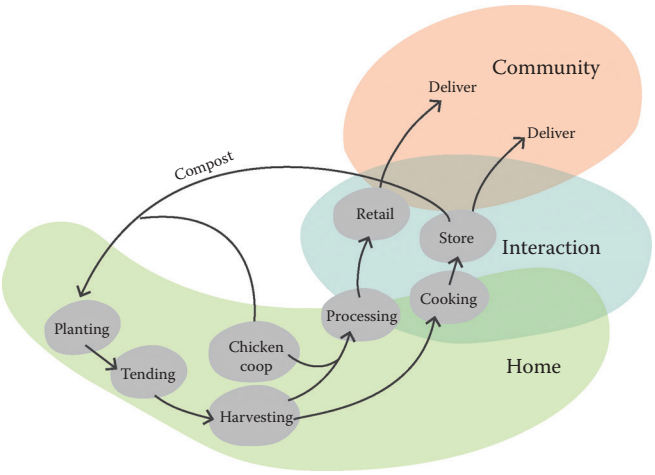


FIGURE 4.27 Food theme diagram.

requirements, ensuring adequate development of the activities, reducing excess waste, and increasing synergies and interactions between inputs and outputs.

In addition to the specific theme clusters, there are general support spaces that exist in all homes and that must respond to the needs of a community of adults with autism. These provide opportunities for integration within the home, with the community, and with family; independence (inside and outside); communication and accessibility; and security and safety (individual and group), all of this located in a healthy and sustainable environment, with possibilities for personal growth and recreation, and supported by technology (Figures 4.28 and 4.29).

4.3.2 Self-Sufficiency

In March 2015, RIBA Competitions launched a design ideas competition on behalf of the Government of Tristan da Cunha. Tristan da Cunha is the most remote inhabited island in the world, located in the South Atlantic Ocean, with around 270 islanders. The island is 1750 miles southwest of Cape Town, and due to the severity of the ocean swells and limitations of the harbor facility, it is only accessible by sea on approximately 60 days per year. The competition was seeking innovative, cost-effective approaches for the redesign and consolidation of the island's government buildings, initiatives to significantly improve the living standards and performance of residential properties, together with improvements to the island's agrarian systems to better support grazing and the year-round growth of fresh produce (http://www.ribacompetitions.com/tristan/).

Our goal was to improve the quality of life of the inhabitants by improving buildings and modes of production with local materials and minimum input from outside the island. Our submission, developed by P La Roche, A Ponce, A Shah, I Chang, T Sam, A Batungbakal, J Wu proposed a community that was self-sustainable, integrating human and natural systems as much as possible. The buildings harness natural forces of the sun and wind. For example, solar energy is used for passive heating, hot water, and electricity in buildings. Solar energy also provides fuel for plants, which are used for food as well as those coming from the ocean and animals, while earth, sand, and volcanic stone would be used as construction materials. Figures 4.30 and 4.31 illustrate how different natural elements can be used to support human requirements with a minimum amount of imports to supplement them.

We keep most of the existing buildings on the island while also adding a new civic center and areas for silvopasture that will increase the supply of wood and grazing with enhanced soil protection and regeneration. New services like a food market, gym, sauna, and showers will improve their quality of life. Urban interventions are shown in Figure 4.32.

In general, we proposed initiatives to improve the general standard and energy performance of all homes so that they are more self-sustaining, with less dependency on outside resources. This would be done via a combination of refurbishment and new-build opportunities. Government buildings on Tristan are also of very simple construction and nearing the end of their useful life. We proposed to replace/refurbish the Administration Office, Island Store, Agriculture, PWD, Telecommunications, Conservation, and Fisheries Departments all in one multifunction building, which we described as a SAW building, a place to store, for public assembly, and to work, consolidating all civic functions under the same roof (Figure 4.33). This building uses elements from the existing vernacular but also incorporates enhanced daylight, well ventilated and insulated with views and improved spatial qualities (Figure 4.34).

4.3.3 Infrastructure

California's buildings are on their way to becoming net-zero energy; however, even though water awareness has increased with the severe drought, there is still little willingness to invest in necessary infrastructure and much has to be done to achieve the same levels of water conservation that already exist for energy.

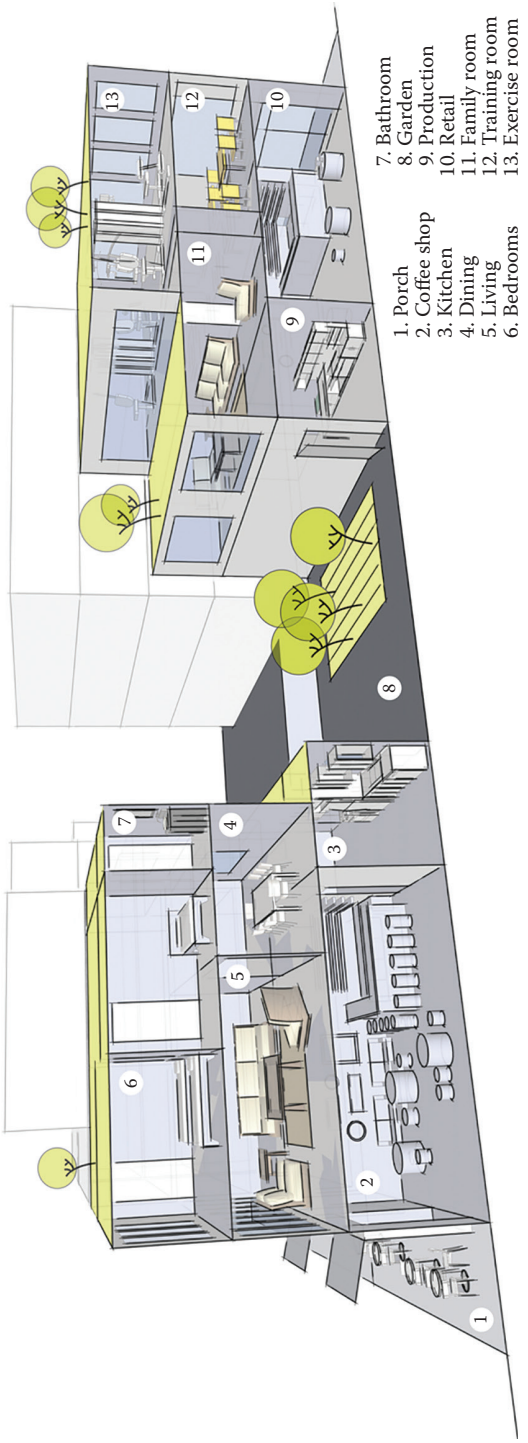


FIGURE 4.28 Layout of spaces responds to themes.

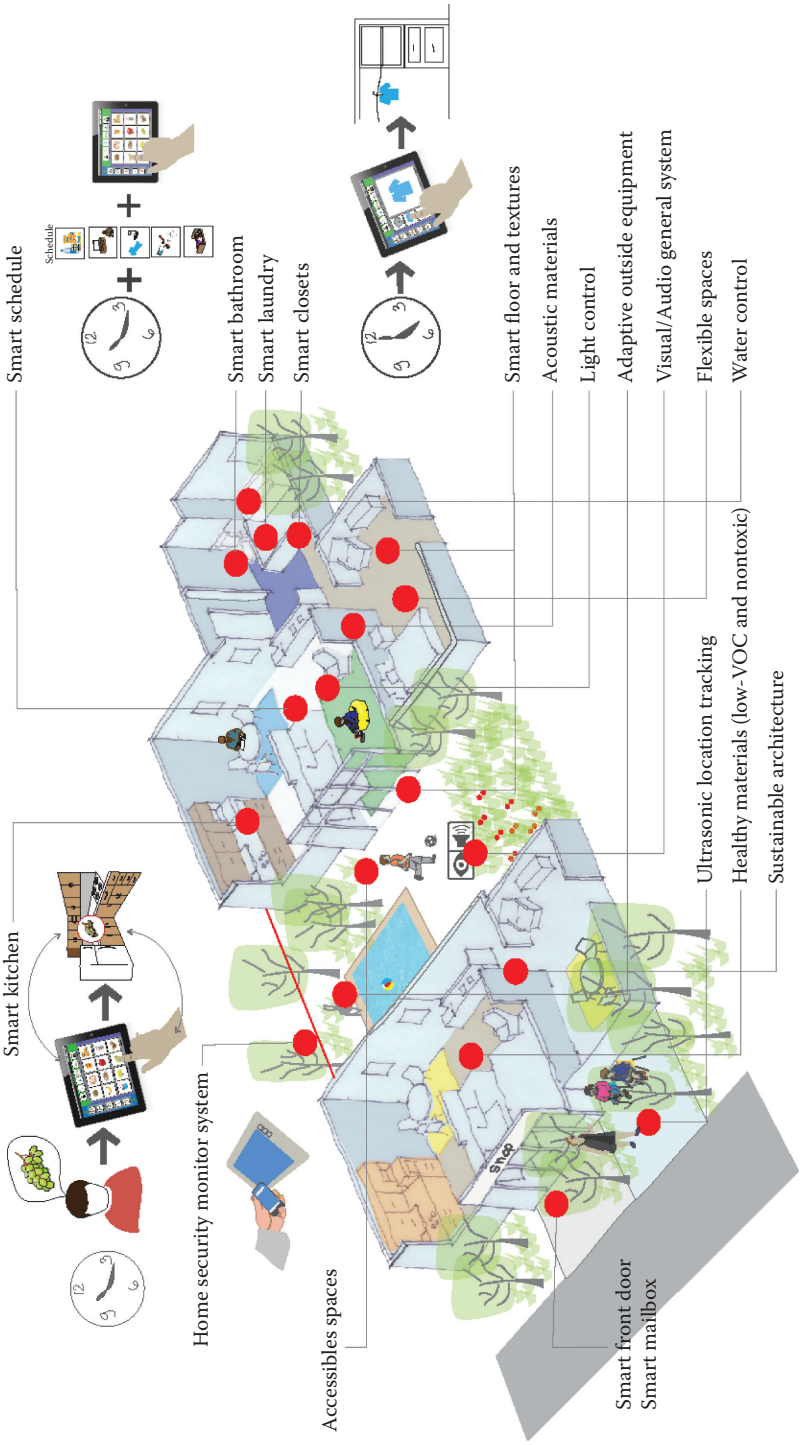


FIGURE 4.29 W2E Home with supportive technology.

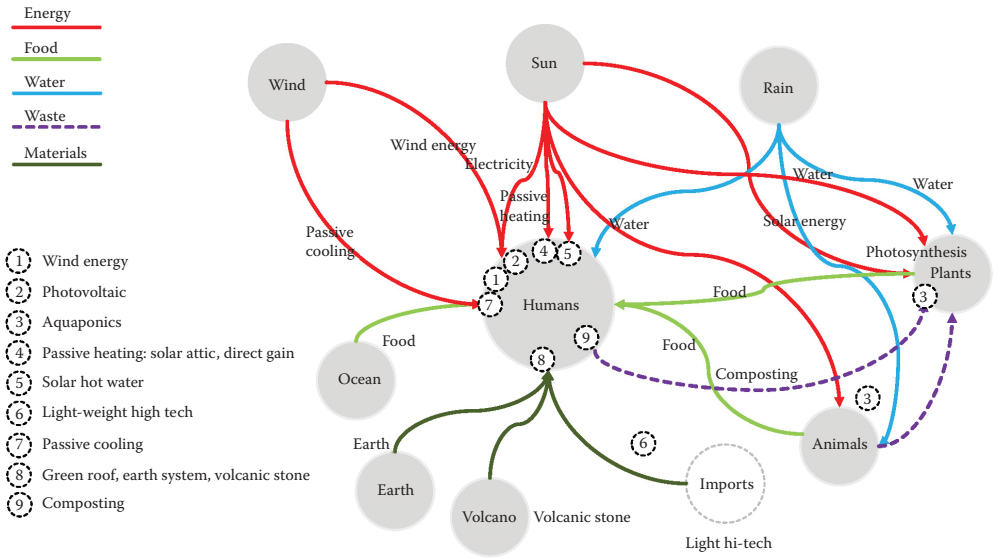


FIGURE 4.30 Conceptual system.

The Land Art Generator Initiative (LAGI) provides a platform for artists, architects, landscape architects, and other creatives working with engineers and scientists to bring forward human-centered solutions for sustainable energy infrastructures that enhance the city as works of public art while cleanly powering thousands of homes (http://www.landartgenerator.org/index.html). Every two years the LAGI international design competition organizes an international competition to reflect on the nature of energy infrastructures and what they can aspire to be in their built form. In 2016 the biennial competition was in Santa Monica, exploring the theme of coastal typologies. Furthermore, to address California's drought, the definition of sustainable infrastructure was expanded to include proposals that could produce drinking water—either in addition to or in place of clean electricity (http://www.landartgenerator.org/competition2016.html).

Our team's proposal for this competition developed by John Eric Chung, Pablo La Roche, Danxi Zou, Jingyan Zhang, Tianyi Deng was called Cnidaria Halitus (Figure 4.35). Our Cnidaria could produce 600,000 L of water per day of potable water for the city of Santa Monica, transforming seawater into potable water, relying completely on solar and tidal energy.

First, the water is filtered and collected from the ocean through a centralized system of pipes that pump it to the interior of each of the boilers located at the focal point of a Fresnel lens. The axis of the Fresnel lenses and the collectors are always tracking the sun in its daily and monthly trajectory across the sky, maximizing heat collection. Multiple collectors absorb an average of 590,000 kWh/d, concentrating this solar energy on each of the boilers, which then evaporate the seawater. The boiler itself consists of a double-glazed envelope, vacuum in between, that allows solar radiation concentrated from the Fresnel lens to enter, while reducing conduction losses, much like an evacuated tube collector. The lower part of the boiler is coated with a selective black paint that increases absorption of solar radiation while its low emissivity and additional insulation in its exterior keeps the heat inside the evaporation chamber. Inside this boiler a network of corrosion-resistant metal alloy pipes is thermally connected to metal alloy plates coated with a heat-selective paint that conducts the liquid inside this chamber. The plates maximize the absorption of solar radiation, while the selective paint minimizes reradiation. All of this energy absorbed inside the evaporation chamber is transmitted by conduction to the water flowing inside the pipes, concentrating it in this small volume of water, which then evaporates and travels to the sides of the Fresnel lens where it is

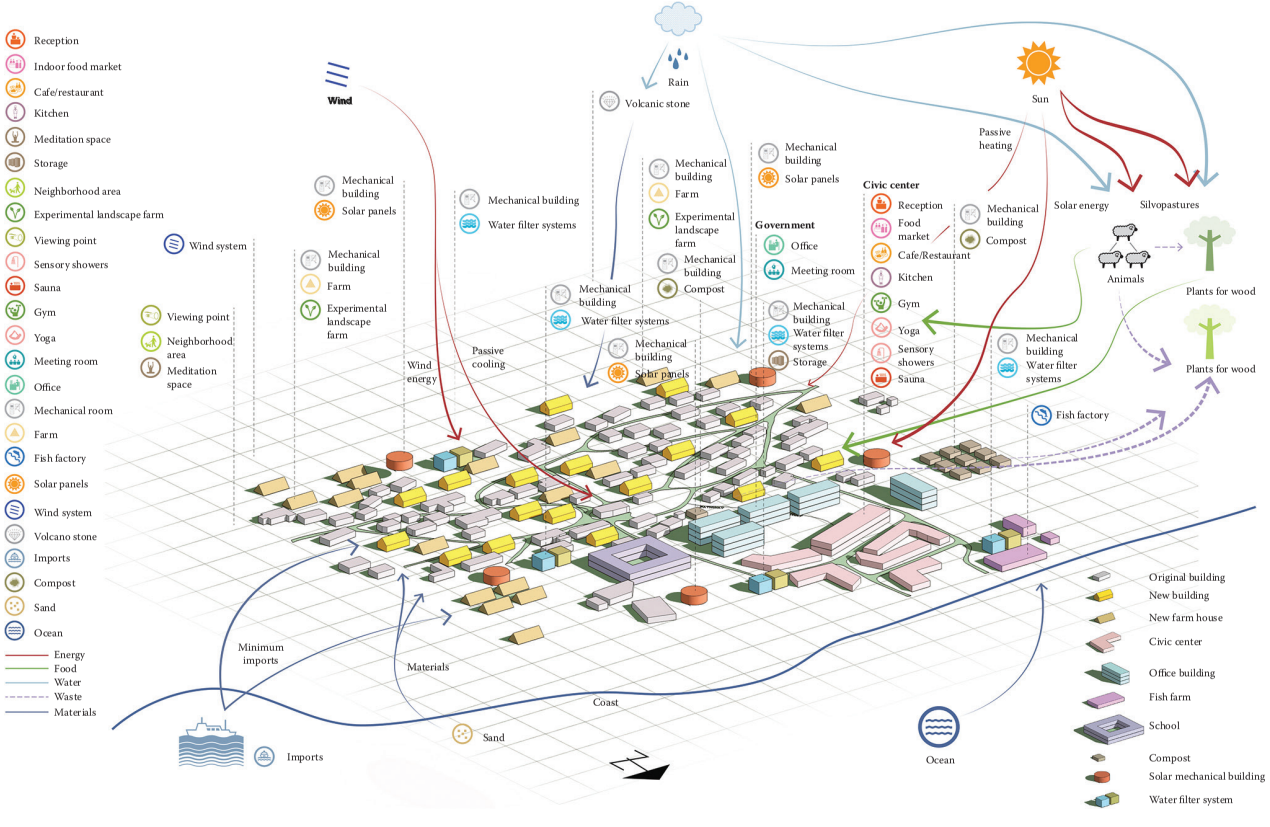


FIGURE 4.31 Proposed system.

Preserved buildings	New buildings
1. Lobster factory	1. New typology
2. Administration	2. Multi-function hall
3. School	3. Market (expansion)
4. Shop	4. Wellness center
5. Post office/tourism centre	5. Research center
6. Church (2)	6. Technology facility
7. Hospital	
8. Prince Philip hall	

FIGURE 4.32 Urban master plan w interventions.

FIGURE 4.33 SAW typology building (Storage, Assembly Work).

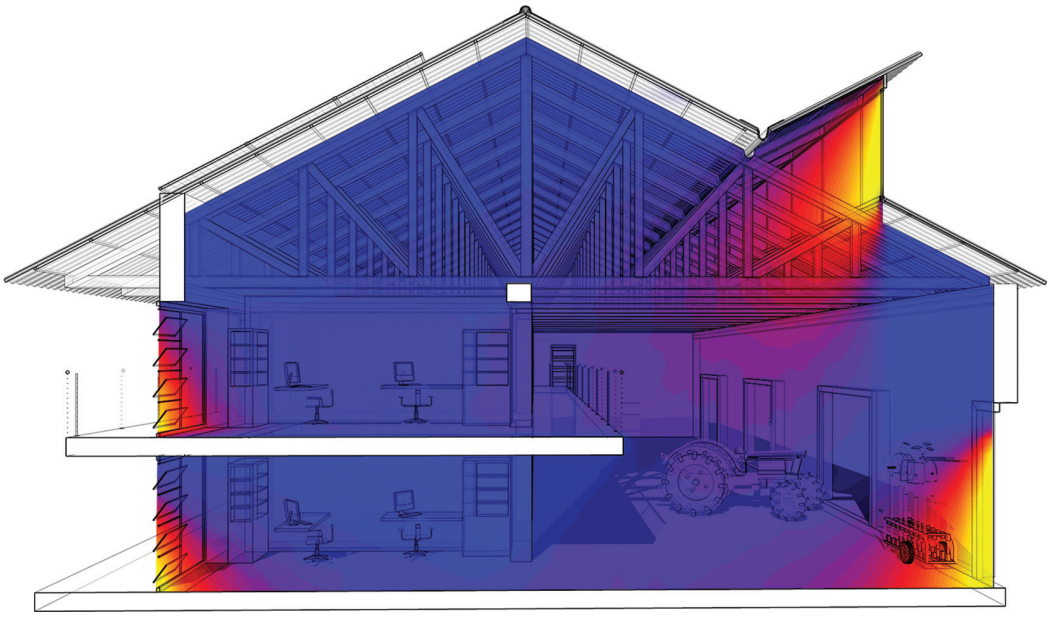


FIGURE 4.34 Improved daylight in SAW building.

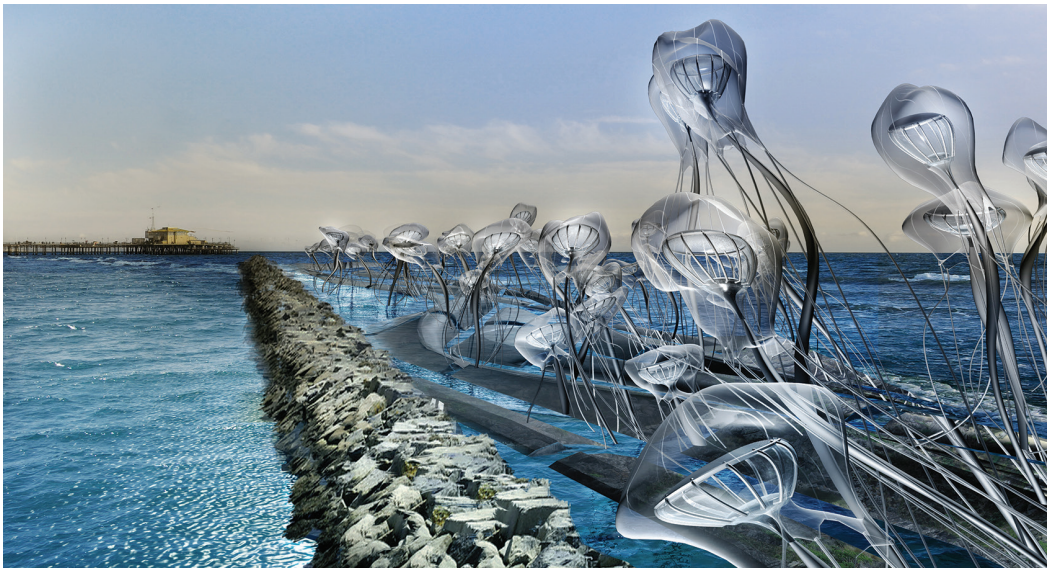


FIGURE 4.35 Cnidaria Halitus.

ejected as vapor inside a double skin. The internal surface of this double skin is made of rigid plexiglass, which is UV and scratch resistant, and also contains the Fresnel lens. The external surface is an ultra-lightweight transparent fabric that expands with the water vapor, further increasing the surface collection area and allowing maximum solar radiation on the boiler. The vapor condenses in the exterior skin—there is a slight reduction in solar gain compensated by increased area—and falls by gravity to collectors and is distributed to the city. Each of these distillers can evaporate about 15,000 L of water per day (Figure 4.36).

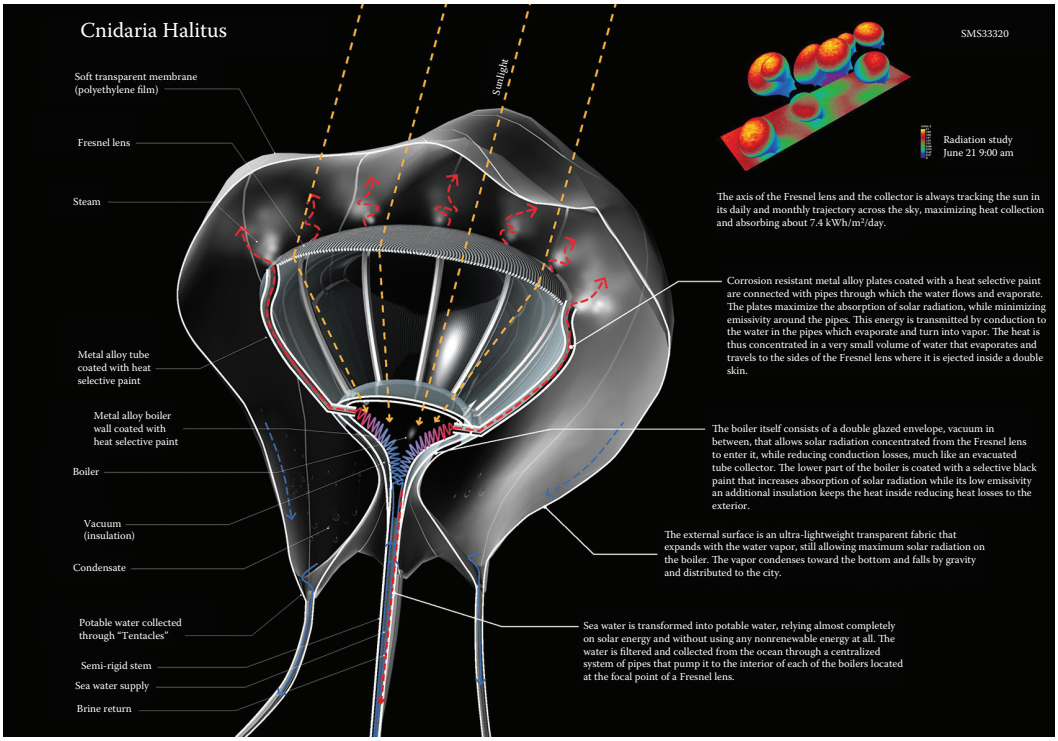


FIGURE 4.36 Cnidaria Halitus section.

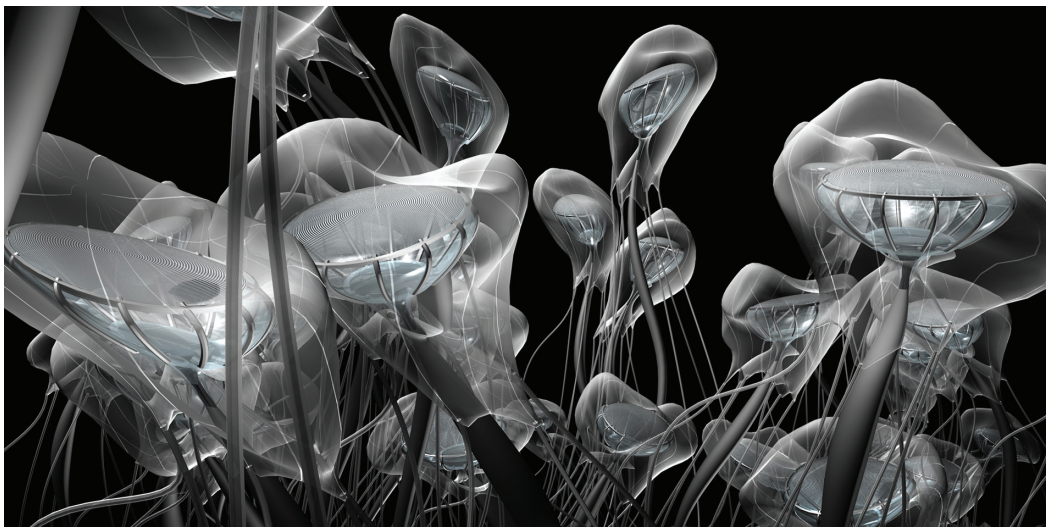


FIGURE 4.37 Cnidaria Halitus.

The breakwater is used to channel the currents and concentrate them in slits, where the turbines are located, harnessing the flowing kinetic energy of the tides to generate electricity. This electricity is used to pump the water up to the boilers and to continue with the heating and evaporation process during the night, also providing an attractive glow during the night. The 40 proposed Cnidaria could generate 220 million liters of drinking water per year, or about 2% of the potable water consumption in the city of Santa Monica (Figure 4.37). More could be added in subsequent phases.

Environmental impact would be minimal; the breakwater is expanded as a usable territory for the community while it is used as an instrument to generate tidal energy. The Cnidaria have no negative environmental impact on the environment.

This project is a conceptual proposal; much work needs to be done to finalize design and eventually test a prototype; however, it illustrates that solutions to an issue do not necessarily have to follow prescribed forms if the principles of systems and energy are understood. Furthermore, this idea, as do the other competition submissions, provides a visible solution to Southern California's water problem, creating awareness, while providing carbon-free potable water from the ocean to the city.

5 Thermal Comfort

Carbon-neutral buildings should provide thermal comfort with minimum energy use and minimum greenhouse gas (GHG) emissions. In the same way that a building that provides an adequate thermal environment with excessive emissions is unethical, a building that reduces emissions at the expense of an uncomfortable and unhealthy environment is unsuccessful. Thus, it is necessary to have a basic understanding of human thermal comfort to achieve a low-carbon, healthy, and thermally comfortable building that is environmentally friendly.

5.1 PSYCHROMETRICS

Clean air is a mixture of 10 gases: nitrogen, oxygen, argon, carbon dioxide, neon, helium, methane (CH_4), krypton, hydrogen, and xenon. Five of these travel alone as atoms, while the rest have atoms bonded together forming molecules. About 78.09% of the air is made out of nitrogen atoms, 20.95% is oxygen, and argon is about 0.53%. Carbon dioxide is about 0.04% (392.39 ppm in 2010; NOAA, 2010) and rising continually. Psychrometry is the science that deals with the study of this mixture, essentially the relationship of these gases with water vapor. This is important because the amount of water vapor in the air affects thermal comfort. The graphic representation of these relationships is the psychrometric chart. Figure 5.1 shows the relationship of these variables with each other in the American Society of Heating, Refrigerating and Air-Conditioning Engineers' (ASHRAE's) psychrometric chart at the sea level.

The psychrometric chart allows us to understand several relationships between concepts. For architectural design, the most important of these concepts to understand are the dry-bulb temperature (DBT), the humidity ratio, the relative humidity, and enthalpy. These concepts are shown in a simplified version of the psychrometric chart (Figure 5.2).

The DBT indicates the amount of heat in the air and is indicated on the horizontal axis (Figure 5.3). For molecules of air, the temperature is directly proportional to the mean kinetic energy of the air molecules. It is usually measured in degrees Celsius, Kelvin, or Farenheit (°C, K, or °F).

The moisture content or absolute humidity indicates the amount of moisture by weight within a given weight of air and is indicated on the vertical axis (Figure 5.4). It can be measured in lbs/lb, kg/kg, or g/kg (units of moisture per unit of dry air). Vapor pressure is linearly related to absolute humidity, so it can also be shown on this scale.

The relative humidity expresses the relationship between the amount of water vapor in the air and the maximum it can hold at that specific temperature and is expressed as a percentage (%). The relative humidity is indicated by curves that converge toward the left side of the psychrometric chart (Figure 5.5). The curves expand upward as the temperature increases toward the right of the chart because the air can hold more water at higher temperatures. The top curve is the saturation line, which indicates the maximum amount of moisture that the air can hold at that specific temperature. If the DBT drops below the saturation line, then condensation occurs. The amount of this condensation can be read vertically on the moisture content scale.

Enthalpy is the heat content of the air relative to 0°C and 0% relative humidity. It is the sum of the latent and sensible heat and is measured in kJ/kg or Btu/lb dry air. Enthalpy has two components, sensible heat and latent heat. Sensible heat increases the DBT of the air at a rate of about 1.005 kJ/kg/K, and latent heat is the heat that is necessary to evaporate liquid water to form the

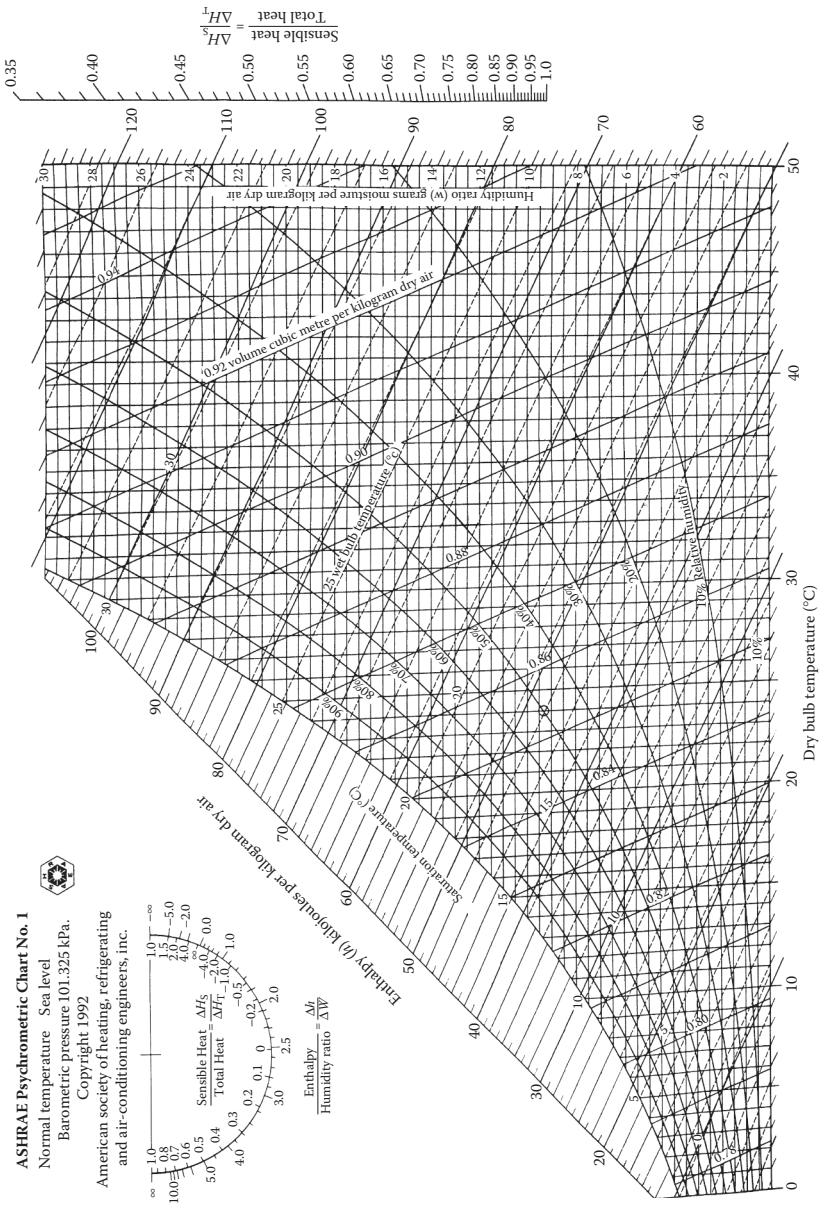


FIGURE 5.1 Psychrometric chart. (From ASHRAE, *Handbook of Fundamentals*, Atlanta, GA, 2005. With permission.)

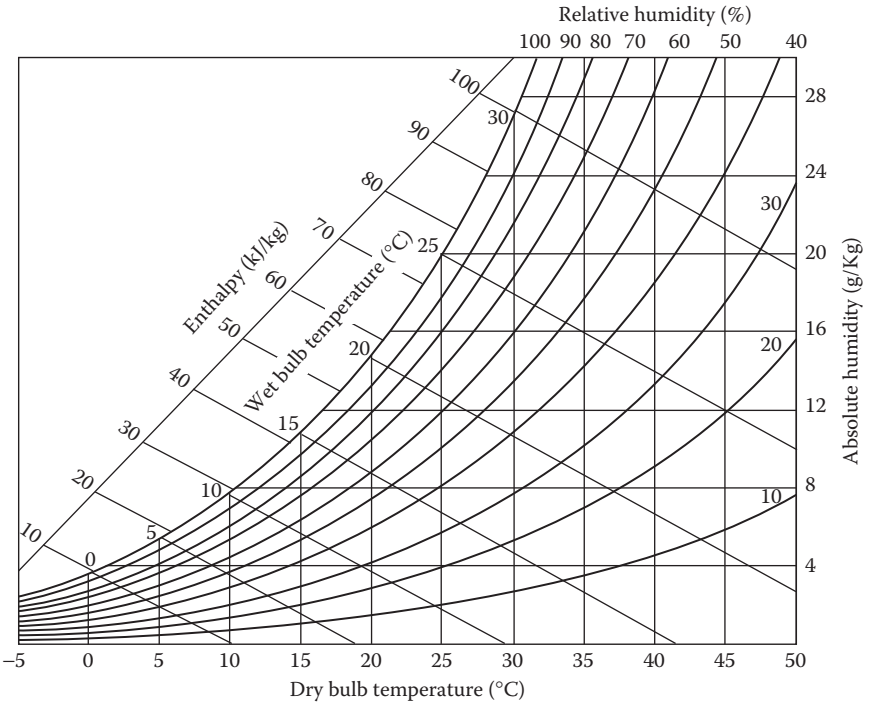


FIGURE 5.2 Simplified psychrometric chart.

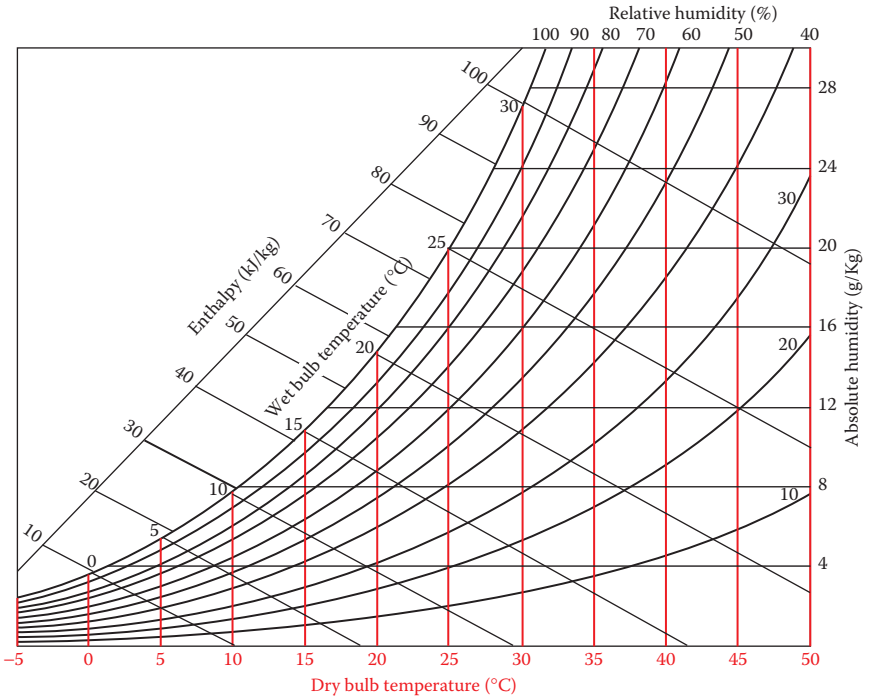


FIGURE 5.3 Dry-bulb temperature in the psychrometric chart.

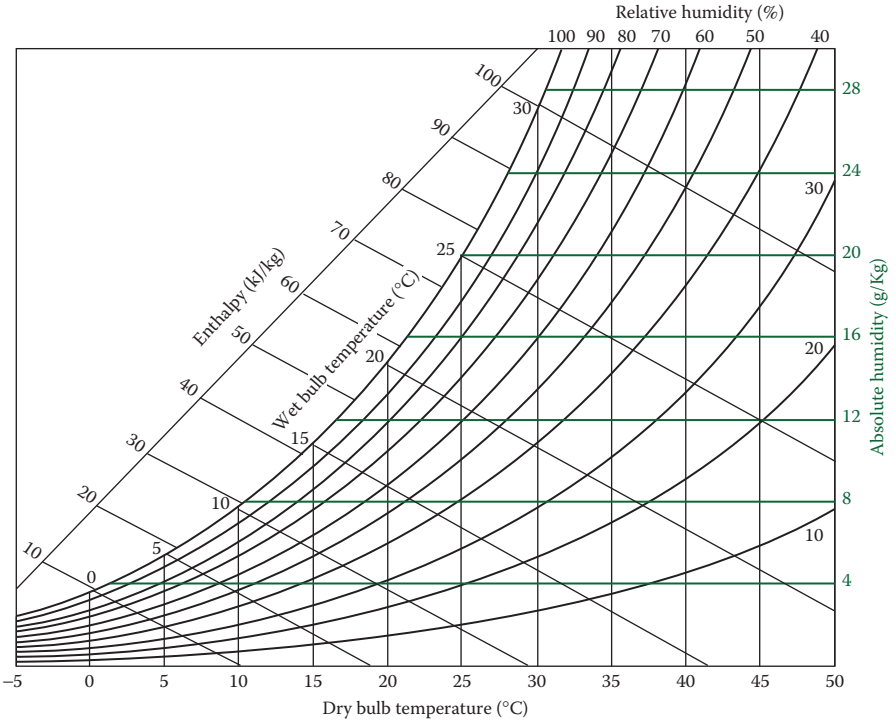


FIGURE 5.4 Moisture content in the psychrometric chart.

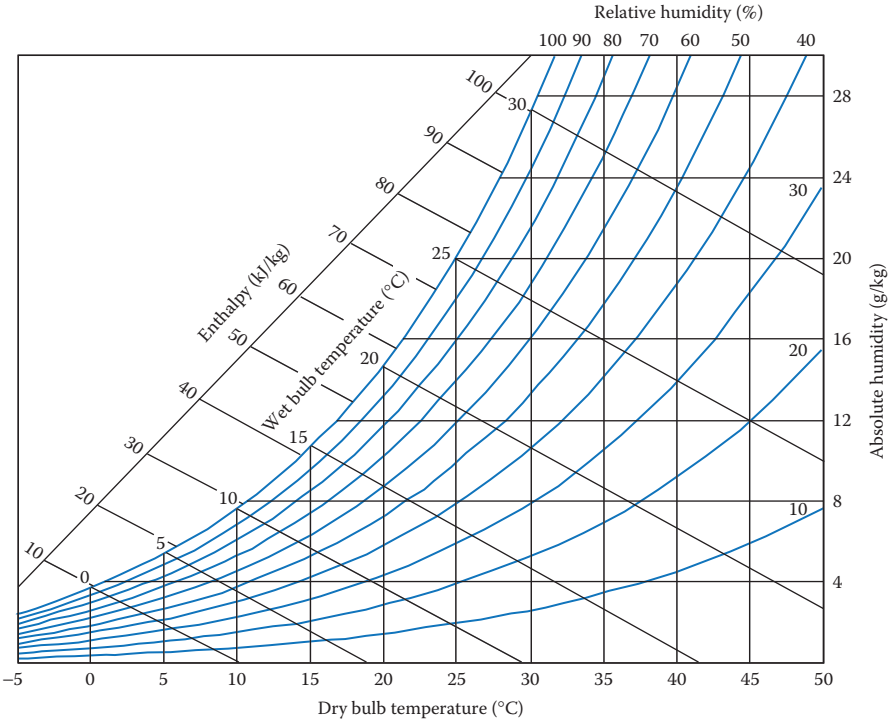


FIGURE 5.5 Relative humidity in the psychrometric chart.

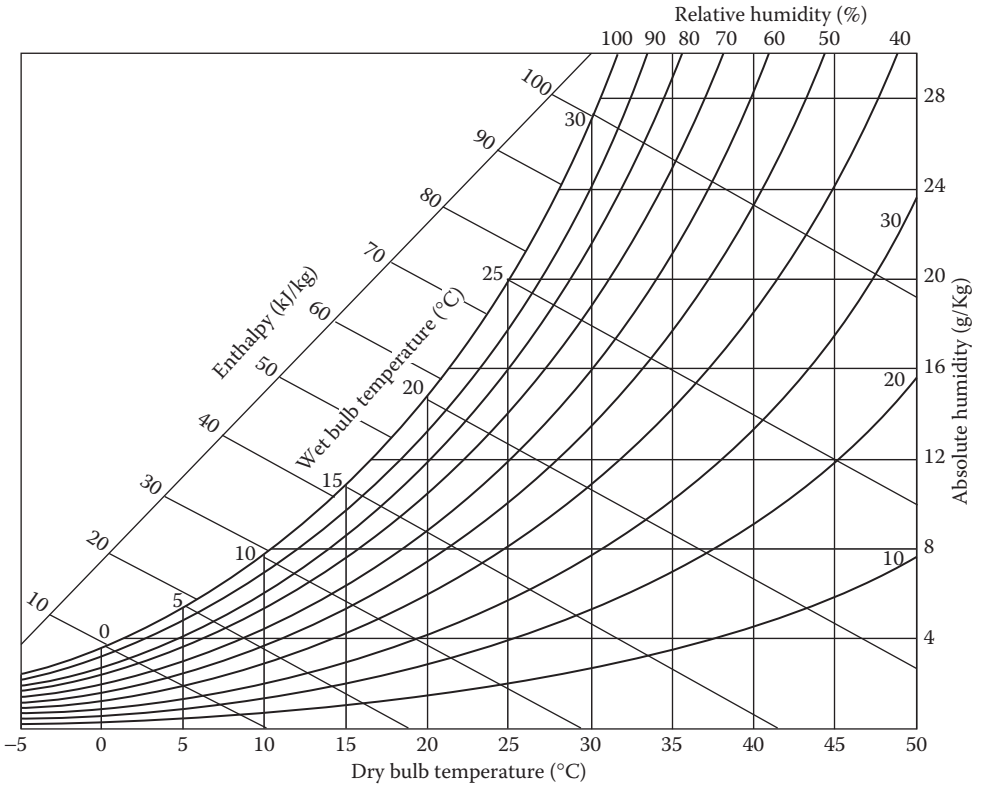


FIGURE 5.6 Enthalpy and wet-bulb temperature in the psychrometric chart.

moisture content of the air. The enthalpy scale is usually indicated outside the body of the chart toward the upper left (Figure 5.6). The wet-bulb temperature lines are almost parallel to the enthalpy lines.

Several psychrometric processes can be plotted on the chart. For designers the most important of these processes are heating, cooling, humidification, and evaporative cooling. Heating the air will move a point horizontally to the right (A to C), and cooling the air will move it horizontally to the left (A to B) (Figure 5.7). There is no change in absolute humidity; however, the relative humidity changes because of the differences in the maximum amount of moisture that the air can hold at different temperatures. If the temperature is cooled to the saturation line, then condensation will occur and the point at which this occurs is the dew point temperature.

When water particles evaporate within a stream of ambient air without a supply of external heat, the temperature of the air is lowered and its moisture content is elevated, while its wet-bulb temperature remains constant (A to B). This change in air temperature, which occurs without addition or extraction of heat from the system, following the enthalpy lines, is called "adiabatic," meaning that the total energy content of the air (sensible plus latent) is kept constant (Figure 5.8). When air is passed through a chemical sorbent such as silica gel, this material removes some of the moisture content, reducing the absolute and relative humidity and increasing its heat content because of the release of heat through this process (A to C).

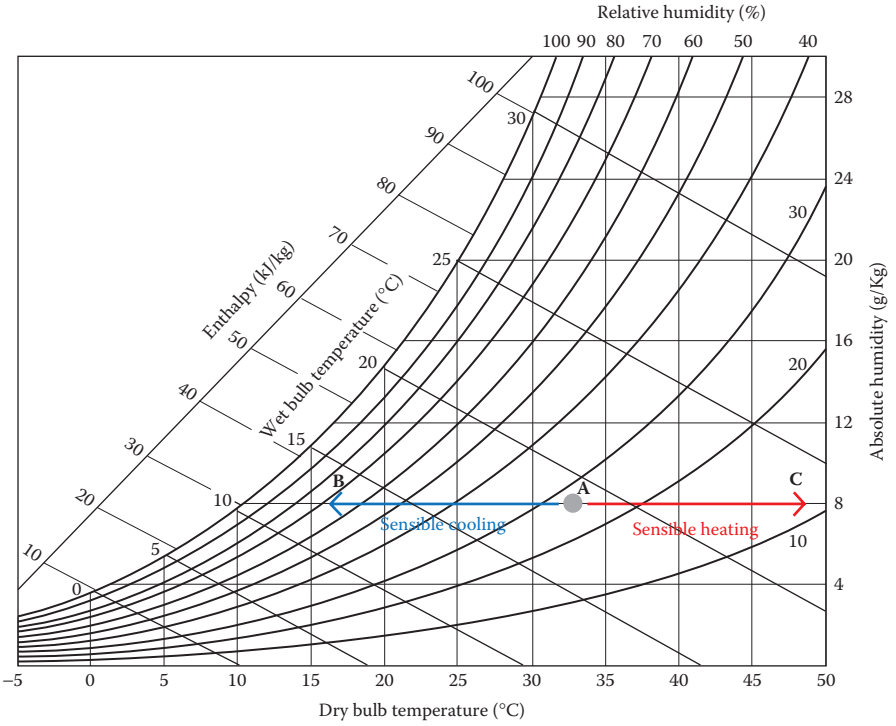


FIGURE 5.7 Sensible heating and sensible cooling in the psychrometric chart.

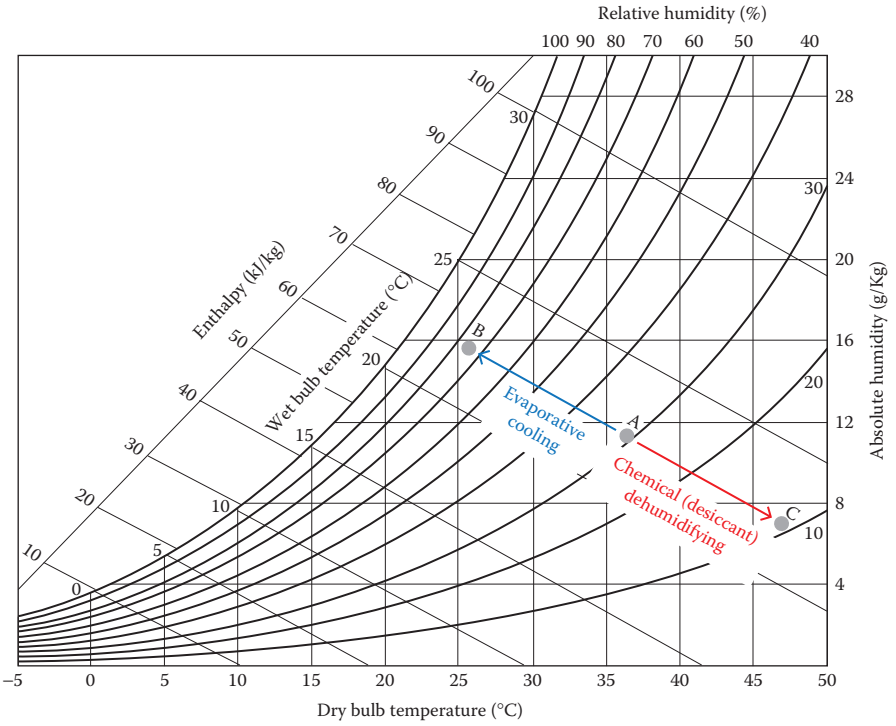


FIGURE 5.8 Adiabatic heating and cooling.

5.2 THERMAL COMFORT

The ASHRAE definition of comfort is "that condition of mind that expresses satisfaction with the thermal environment" (ASHRAE, 2005). In general, comfort occurs when body temperatures are held within specific narrow ranges, skin moisture is low, and the physiological effort of regulation is minimized. We are comfortable when we do not have to think about it.

The human being burns food as fuel and generates heat. About 20% of the energy produced during this biological process is turned into work and the rest is dissipated as waste heat. If the body is not able to dissipate this heat, it will overheat. Heat-flow mechanisms (conduction, radiation, and convection) dissipate heat and maintain an optimum operating temperature in our body.

5.2.1 Heat Balance

To operate adequately, the human body must be in heat balance. Warm-blooded animals require a very constant temperature to operate, and our body tries to maintain a deep body temperature of about 37°C (98.6°F) and a skin temperature of about 33°C (91.4°F). If the human body heats up too much, then it will not function properly. At about 38°C (100°F) our body begins to sweat, at about 40°C (104°F) we have a nauseous feeling, at about 42°C (107.6°F) we pass out, and if our body temperature reaches 44°C (111°F), we will have brain damage. If our body cools down too much, then it will not function properly either. At about 35°C (95°F) we start shivering and have goose bumps, at about 29°C (84.2°F) we lose the power of speech, at about 22°C (71.6°F) the body is too cold for most situations, and at about 15°C (59°F) it is virtually impossible to recover.

To maintain optimum operating conditions and avoid overheating or overcooling, the heat that is generated by the metabolism or gained from the environment must be dissipated at the same rate that it is gained. The body is homoeothermic, which means that it has several physiological regulatory mechanisms to control heat dissipation. When the air is warm, the body responds by vasodilation: Subcutaneous blood vessels expand and increase the skin blood supply and the skin temperature, which in turn increases heat dissipation. If this is not enough, then the body will begin to sweat (evaporative cooling) using body heat to evaporate sweat. If this is not sufficient to restore balance, then body heating or hyperthermia, which is insufficient heat loss, will occur. When the air is cold, the response is vasoconstriction, reducing blood circulation to the skin and thus lowering the skin temperature and the rate of heat dissipation. Pores are also closed, reducing surface evaporation. Shivering also increases the production of metabolic heat. If these mechanisms are not sufficient to reduce heat losses, then the body will cool and hypothermia (i.e., excessive heat loss) will occur.

The sensation of comfort depends a great deal on the ease with which the body is able to regulate the balance. The body will always be producing energy, and there will always be heat gains and losses; however, the body temperature must remain stable. The balance between heat gains and losses is expressed in the following equation:

$$\Delta S = M \pm R_{\mathrm{d}} \pm C_{\mathrm{v}} \pm C_{\mathrm{d}} - E_{\mathrm{v}} \tag{5.1}$$

where:

ΔS is the change in stored heat
M is the metabolic heat production
R_{d} is the net radiation exchange
C_{v} is the convection
C_{d} is the conduction
E_{v} is the evaporation

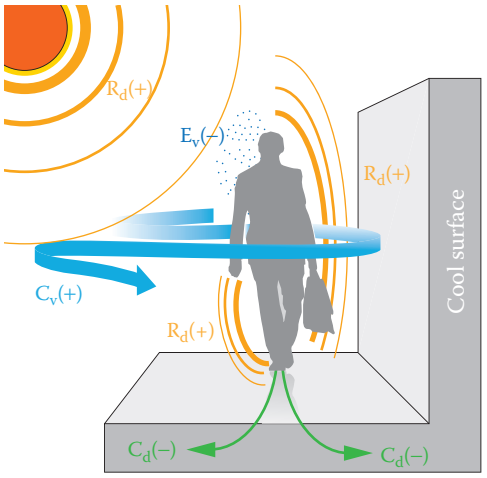


FIGURE 5.9 Heat transfer mechanisms.

Evaporation is always negative (heat dissipation mechanisms), metabolic heat production is always positive (heating mechanisms), and the rest can be positive or negative depending on the direction of the heat flow. Figure 5.9 shows an example in which the temperature of the body is higher than the temperature of the floor, so the heat is flowing from the body to the floor (negative); the temperature of the wall is lower than the temperature of the body, so the heat is flowing from the body to the wall (negative); the temperature of the air is warmer than the temperature of the body (positive heat flow); and the net radiant exchange between the body and the sun is positive. For the body to be in equilibrium, ΔS must be zero. This is a precondition, but not the only variable that determines thermal comfort.

The human body maintains a balance with its environment and must dissipate the heat that is generated or absorbed by it. At about 21°C (70°F), the body heat losses are 40% by convection, 20% by evaporation, 40% by radiation, and just a little by conduction. However, these ratios are affected by air temperature; as the air temperature increases, the amount of heat lost by evaporation increases, and above a temperature of 37°C (98.6°F) sweating must dissipate all the heat that is generated by the body plus the heat that is added by radiation, convection, and conduction (Figure 5.10).

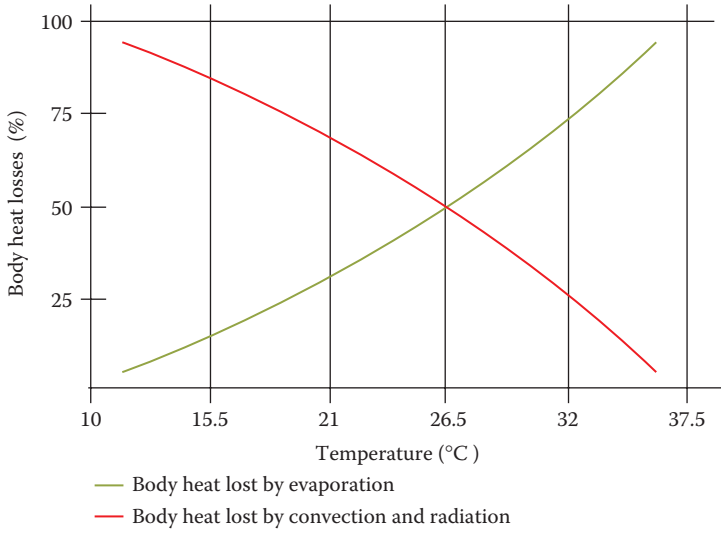


FIGURE 5.10 Heat dissipation for a person at rest at different temperatures.

5.2.2 Variables That Affect Thermal Comfort

Thermal comfort is affected by several factors that affect the rate of heat dissipation from the body and are usually classified as environmental or personal factors. There are also additional contributing factors that affect thermal comfort.

The environmental factors are air temperature, radiation, air motion, and relative humidity. Air temperature measured by the DBT is probably the single most important environmental factor, because together with air movement it affects the rate of convective heat dissipation. The air temperature is measured using a dry-bulb thermometer.

Radiation affects thermal comfort through the radiant exchanges between the body and the surfaces that surround it. The magnitude of this exchange is affected by the difference in temperature between our body and the exchange surface and the view angle between this surface and our body. A larger angle or a higher temperature difference between the two surfaces will produce a larger radiant exchange (Figures 5.11 and 5.12) with new radiation always moving from a higher to a lower temperature. The thermal effect of the surfaces surrounding and affecting an object is indicated by the mean radiant temperature (MRT). This is measured with a globe thermometer, which is usually a matte black copper sphere 15 cm in diameter that responds to the effect of radiation flows from the surrounding surfaces. If the temperature of the globe thermometer is higher than the DBT, then the

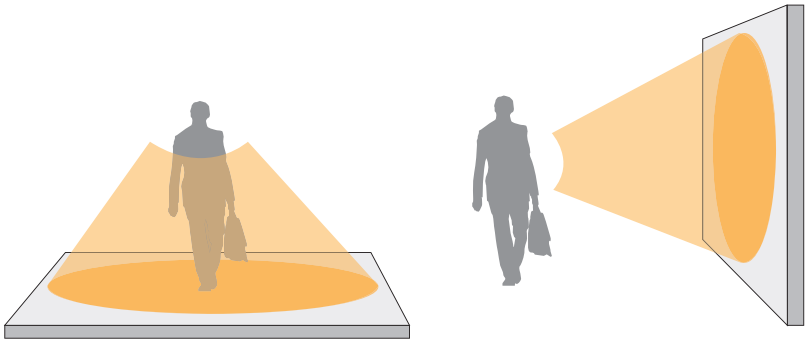


FIGURE 5.11 Larger angle of exposure increases radiant exchange.

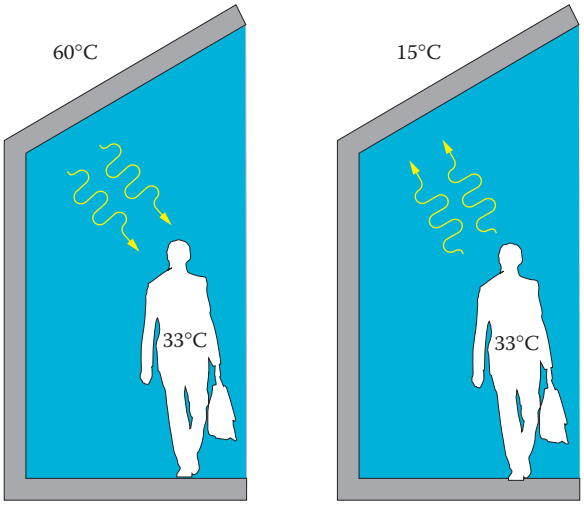


FIGURE 5.12 Higher temperature different increases radiant exchange.

surrounding surfaces are warmer than the air; if it is lower, then the surface temperatures are lower than the temperature of the air.

Air motion affects the evaporation of moisture from the skin. A higher air velocity increases the evaporative cooling effect and reduces the surface resistance of the body. Air movement is one of the most useful strategies to cool the body in a hot and humid climate and is measured in meters per second (m/s) or feet per minute (ft/min). Higher air velocities, up to about 2 m/s, can increase the sensation of thermal comfort in overheated conditions.

Relative humidity affects the evaporation rate from the skin. A lower relative humidity of the air allows more sweat to evaporate and cool the skin, whereas higher relative humidity (i.e., above 70%) makes it more difficult for the sweat to evaporate because the air's moisture content is already elevated. In humid climates, sweat will not evaporate because the air is already close to the saturation level. Very low relative humidity (i.e., below 30%) is also uncomfortable because of its drying effect on the mucous membranes. Humidity between 30% and 60% is usually considered acceptable because it has a limited effect on thermal comfort.

The personal variables that affect thermal comfort are the metabolic rate (activity) and clothing. The metabolic rate is the heat generated by the body. Heat production in the human body can be of two kinds: (1) basal metabolism due to biological processes that are continuous and nonconscious and are in the range of about 60 W/m^2 of body surface area (about 100 W in a typical body); and (2) muscular metabolism, which is produced while carrying out work that is consciously controllable (except shivering). Metabolic rate can be expressed as power density in mets or W/m^2, where 1 met = 58.2 W/m^2 of body surface area (18.4 Btu/h/ft^2 of body surface area) and varies depending on the activity level of the body (Figure 5.13, Table 5.1).

Clothing is insulation around the body, which means that it can be measured in the same units of thermal transmittance (U-value) W/m^{2}K. To simplify the units when studying thermal comfort, a unit called the clo has been created. One clo has the U-value of 6.45 W/m^{2}K, which is equal to a resistance of 0.155 m^{2}K/W spread over the whole body. It is probably easier to visualize by understanding that 1 clo is equivalent to the insulating value of trousers, T-shirt, long-sleeve shirt, plus long-sleeve sweater. Table 5.2 lists clo values for several typical clothing ensembles. Additional tables in the *Handbook of Fundamentals* (ASHRAE, 2009) describe the insulation values of individual ensembles, which can be used to calculate the clo value with more precision.

met	0.8	1.2	1.2	1.9	7	11
W/m2	46	70	70	110	406	638

FIGURE 5.13 Activity levels and metabolic rates.

TABLE 5.1
Rates of Metabolic Heat

Activity	Btu/h/ft²	W/m²	Met*
Resting			
Sleeping	13	40	0.7
Reclining	15	45	0.8
Seated, quiet	18	60	1.0
Standing, relaxed	22	70	1.2
Walking (on level surface)			
2.9 fps (2 mph)	37	115	2.0
4.4 fps (3 mph)	48	150	2.6
5.9 fps (4 mph)	70	220	3.8
Office activities			
Seated, reading or writing	18	60	1.0
Typing	20	65	1.1
Filing, seated	22	70	1.2
Filing, standing	26	80	1.4
Walking about	31	100	1.7
Lifting/packing	39	120	2.1
Driving/Flying			
Car	18–37	60–115	1.0–2.0
Aircraft, routine	22	70	1.2
Aircraft, instrument landing	33	105	1.8
Aircraft, combat	44	140	2.4
Heavy vehicle	59	185	3.2
Miscellaneous occupational activities			
Cooking	29–37	95–115	1.6–2.0
House cleaning	37–63	115–200	2.0–3.4
Seated, heavy limb movement	41	130	2.2
Machine work			
Sawing (table saw)	33	105	1.8
Light (electrical industry)	37–44	115–140	2.0–2.4
Heavy	74	235	4.0
Handling 110-lb bags	74	235	4.0
Pick and shovel work	74–88	235–280	4.0–4.8
Miscellaneous leisure activities			
Dancing, social	44–81	140–255	2.4–4.4
Calisthenics/exercise	55–74	175–235	3.0–4.0
Tennis, singles	66–74	210–270	3.6–4.0
Basketball	90–140	290–440	5.0–7.6
Wrestling, competitive	130–130	410–505	7.0–8.7

Source: *ASHRAE Standard 55-2004, Thermal Environmental Conditions for Human Occupancy*, ASHRAE, Atlanta, GA, 2004.
Note: MET: Metabolic heat rate

In addition to personal and environmental factors, other contributing factors mostly affect the metabolic rate. Food and drink influence the amount of energy that must be dissipated. Acclimatization includes short-term physiological and long-term endocrine adjustments to climate. Body form and mass affect the metabolic rate. The heat production is proportional to the amount of body mass; more mass produces more heat and the heat dissipation is proportional to the body surface area.

TABLE 5.2
Clothing Insulation Values for Typical Ensembles

Clothing Description	Garments Included[a]	(clo)
Trousers	1. Trousers, short-sleeve shirt	0.57
	2. Trousers, long-sleeve shirt	0.61
	3. Number 2 plus suit jacket	0.96
	4. Number 2 plus suit jacket, vest, T-shirt	1.14
	5. Number 2 plus long-sleeve sweater, T-shirt	1.01
	6. Number 5 plus suit jacket, long underwear bottoms	1.30
Skirts and dresses	7. Knee-length skirt, short-sleeve shirt (sandals)	0.54
	8. Knee-length skirt, long-sleeve shirt, full slip	0.67
	9. Knee-length skirt, long-sleeve shirt, half-slip, long-sleeve sweater	1.10
	10. Knee-length skirt, long-sleeve shirt, half-slip, suit jacket	1.04
	11. Ankle-length skirt, long-sleeve shirt, suit jacket	1.10
Shorts	12. Walking shorts, short-sleeve shirt	0.36
Overalls and coveralls	13. Long-sleeve coveralls, T-shirt	0.72
	14. Overalls, long-sleeve shirt, T-shirt	0.89
	15. Insulated coveralls, long-sleeve thermal underwear tops and bottoms	1.37
Athletic	16. Sweat pants, long-sleeve sweatshirt	0.74
Sleepwear	17. Long-sleeve pajama tops, long pajama trousers, short three-quarter length robe (slippers, no socks)	0.96

Source: *ASHRAE Standard 55-2004, Thermal Environmental Conditions for Human Occupancy*, ASHRAE, Atlanta, GA, 2004.

[a] All clothing ensembles, except where otherwise indicated in parentheses, include shoes, socks, and underwear. All skirt/dress clothing ensembles include pantyhose and no additional socks.

Thus, a person with a higher surface-to-volume ratio can dissipate more heat and has more tolerance to higher temperatures. Subcutaneous fat is an insulating layer. The elderly have narrower comfort ranges because their adjustment mechanisms are not working as efficiently, making it more important to provide them with an appropriate comfort zone.

Some authors now include psychological factors such as color, texture, sound, light, movement, and aroma; however, it is difficult to find scientific evidence that demonstrates the effect of these variables.

5.3 ENVIRONMENTAL AND COMFORT INDICES

Environmental and comfort indices simplify the description of the thermal environment and the stress that it imposes on the human body because they combine two or more parameters (e.g., air temperature, mean radiant temperature, humidity, and air velocity) into a single variable. Many environmental and comfort indices have been developed over the years, and their discussion is outside the scope of this book. Only two will be discussed in this section.

The operative temperature is a simple and easy-to-use environmental index that combines into a single number the effects of DBT, radiant temperature, and air motion on the sensation of warmth or cold felt by the human body. Without considering air velocities, the simplest, though not perfectly accurate, way to calculate operative temperature at low air velocities is to average the DBT and the mean radiant temperature (Equation 5.2). The relationship indicated by Equation 5.2 is affected by the clothing level. If the subject is dressed lightly as is customary in a hot climate, the radiant effect is higher than the effect of the air temperature.

TABLE 5.3
Equations for Predicting Thermal Sensation (Y) of Men, Women, and Men and Women Combined

Exposure Period in Hours	Sex	Regression Equations t = dry-bulb temperature, °C p = vapor pressure, kPa
1.0	Male	$Y = 0.220t + 0.233p - 5.673$
	Female	$Y = 0.272t + 0.248p - 7.245$
	Combined	$Y = 0.245t + 0.248p - 6.475$
2.0	Male	$Y = 0.221t + 0.270p - 6.024$
	Female	$Y = 0.283t + 0.210p - 7.694$
	Combined	$Y = 0.252t + 0.240p - 6.859$
3.0	Male	$Y = 0.212t + 0.293p - 5.949$
	Female	$Y = 0.275t + 0.255p - 8.622$
	Combined	$Y = 0.243t + 0.278p - 6.802$

Source: *ASHRAE, Handbook of Fundamentals,* ASHRAE, Atlanta, GA, 2005. (With permission.)

$$\text{OT} = \frac{(\text{DBT} + \text{MRT})}{2} \tag{5.2}$$

where:
OT is the operative temperature
DBT is the dry-bulb temperature
MRT is the mean radiant temperature

Other equations combine several environmental variables to define a comfort scale. The most important of these is the predicted mean vote (PMV), which predicts the comfort sensation and the degree of discomfort (thermal dissatisfaction) of people exposed to moderate thermal environments. PMV is discussed in the next section.

Another set of equations to predict thermal sensation was developed by Rohles and Nevins (1971) and used by ASHRAE (2005) to predict thermal sensation as a function of the exposure period, DBT, and vapor pressure. The author developed different equations for men and women to predict the thermal comfort sensation (Table 5.3). The ideal value for the comfort sensation (Y) is zero, and in these equations there are several assumptions: the activity level is sedentary, clothing is 0.5 clo, MRT = DBT, and air velocity is below 0.2 m/s.

5.4 COMFORT MODELS

The two main theories of comfort are the heat balance or physiological approach and the adaptive approach. In simple terms, the physiological or heat balance model states that humans are all the same and that comfort on all subjects can be explained by a physiological approach. In this model the comfort zone is the same for all without considering location and adaptation. However, the adaptive model states that in occupant-controlled, naturally conditioned spaces, the thermal response and thus the comfort zone are affected by outdoor climate.

5.4.1 Physiological Comfort Model

The physiological comfort model is best exemplified by the PMV/PPD model, in which PPD is the predicted percent of dissatisfied people at each PMV; the model uses the Fanger PMV formula.

PMV establishes a thermal strain based on steady-state heat transfer between the body and the environment and assigns a comfort vote to that amount of strain.

The original data to develop Fanger's PMV model were collected by subjecting a large number of people to different conditions within a climate chamber and having them select a position on the scale that best described their comfort sensation. A mathematical model of the relationship among all the environmental and physiological factors considered was then derived from the data. The PMV is the average comfort vote predicted by a theoretical index for a group of subjects when subjected to a particular set of environmental conditions. The PMV uses a seven-point thermal scale that runs from cold (–3) to hot (+3) with zero as the ideal. Lower or higher values are possible. From the PMV, the PPD can be determined. As PMV moves away from zero in either the positive or the negative direction, PPD increases. The maximum number of people that could be dissatisfied with their comfort conditions is 100%. However, as you can never please everybody even under optimum conditions, the minimum PPD number even under optimum comfort conditions is 5%. Fanger's method is prevalent in most thermal comfort standards such as ISO 7730. This standard predicts thermal comfort comparing four physical variables, air temperature, air velocity, mean radiant temperature, and relative humidity with two personal variables—clothing insulation and activity level (Fanger, 1967).

A commonly used method to determine if thermal conditions are comfortable is to plot them in a psychrometric chart with the comfort zone plotted in it. An example is ASHRAE's comfort zone for typical indoor environments, which uses operative temperature and humidity ratio (Figure 5.14). ASHRAE standard 55-2004 states that 80% of occupants would find these conditions acceptable. This value is based on 10% dissatisfaction criteria for whole-body thermal comfort that uses the PMV–PPD index plus an additional 10% dissatisfaction that may occur from partial body thermal discomfort. Two comfort zones are indicated in this figure, one for 0.5 clo (summer clothing) and one for 1.0 clo (indoor winter clothing). These zones are valid when air speeds are below 0.20 m/s, and the activity level of the occupants is moderate or low with a metabolic rate between 1.0 met and 1.3 mets.

5.4.2 Adaptive Comfort Model

Researchers doing field investigations with subjects engaged in typical daily activities in their environments, instead of experimental chambers, have found that the subjects' responses in familiar daily situations were different than the predictions using the PMV model, especially when the building was not mechanically heated or cooled. Even though these field studies do not have the scientific rigor of laboratory experiments, they are more immediately relevant to typical living or working conditions. Some authors (Fanger and Toftum, 2002) have tried to explain these differences as differences in expectations in terms of their exposure level to buildings that are mechanically heated and cooled.

Thermal neutrality temperature (T_n) is the air temperature at which a large group of people would not feel hot or cold and the body would be under minimal thermal stress. Probably the first review of available field data that found a statistical relationship between mean levels of DBT and thermal neutrality temperature was done by Humpreys as far back as 1975. In 1981, Auliciems used a larger database and also found a correlation between the thermal neutrality in free-running buildings and the outdoor average temperature (Figure 5.15). This correlation was valid for temperatures between 18°C (64.4°F) and 28°C (82.4°F) (Auliciems and Szokolay, 1997) expressed in the following equation:

$$T_n = 17.6 + 0.31T_{\text{ave}} \tag{5.3}$$

where:

T_n is the thermal neutrality temperature

T_{ave} is the outdoor average dry-bulb temperature

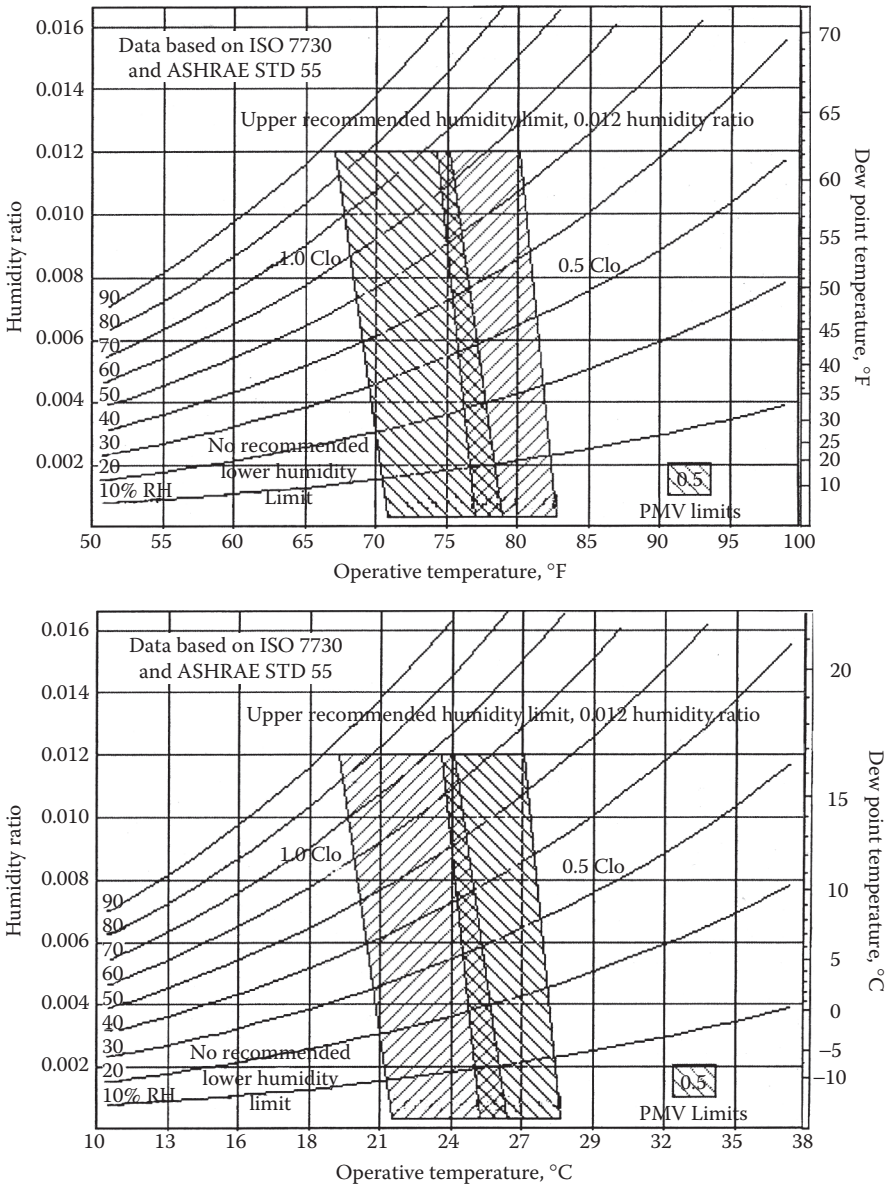


FIGURE 5.14 Acceptable range of operative temperature and humidity for occupants that have metabolic rates between 1.0 and 1.3 met, clothing is between 0.5 clo and 1.0 clo, and air speeds are under 0.2 m/s. (From *ASHRAE Standard 55-2004, Thermal Environmental Conditions for Human Occupancy*, ASHRAE, Atlanta, GA, 2004.)

Griffiths (1990) and Nicol and Roaf (1996) found similar correlations between the neutrality temperature and the outdoor average temperature. In general these equations are valid when the outdoor temperature is between 17°C (62.6°F) and 30°C (86°F). The comfort zone lies between 2°C above and below the neutral temperature. De Dear and Brager (1998) examined the relationship between thermal comfort and indoor and outdoor temperatures in a database of 21,000 observations from 160 buildings worldwide. They found that the PMV model fully explained adaptation in buildings with heating, ventilating and air conditioning (HVAC) systems, but occupants in naturally ventilated buildings were tolerant of a significantly wider range of temperatures. They explained

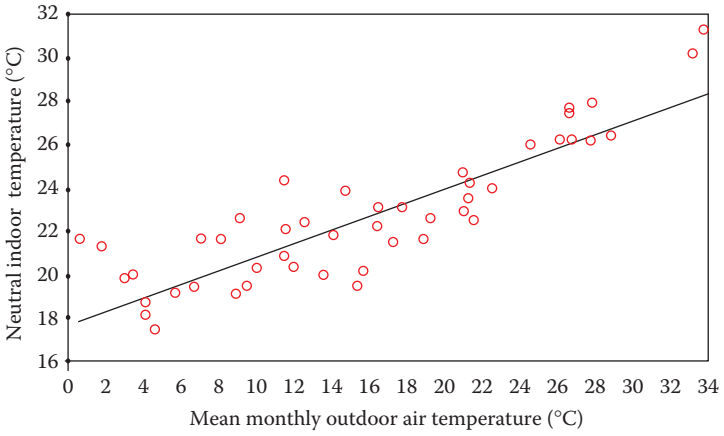


FIGURE 5.15 Auliciems's correlation of indoor neutrality with monthly mean outdoor temperature. (From Auliciems, A. and Szokolay, S., *Thermal Comfort*, PLEA Notes 3, Brisbane, Australia, Department of Architecture, University of Queensland, 1997.)

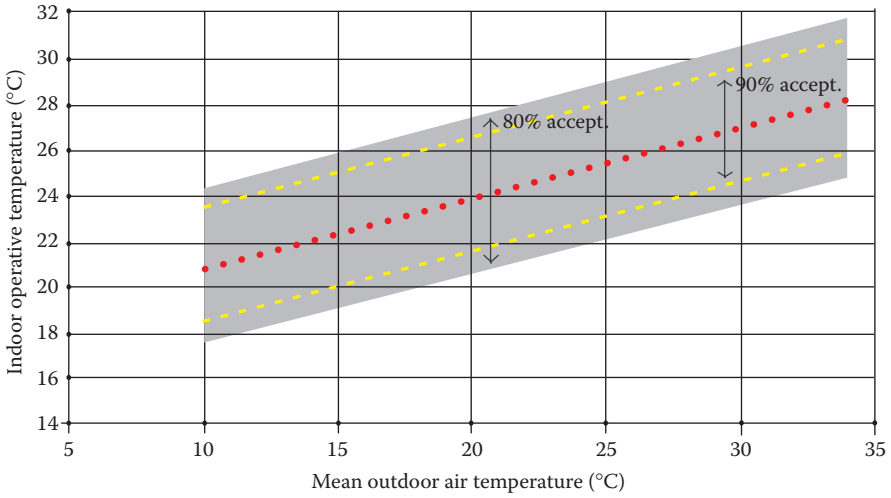


FIGURE 5.16 Acceptable operative temperature ranges for naturally conditioned spaces. (From *ASHRAE Standard 55-2004, Thermal Environmental Conditions for Human Occupancy*, ASHRAE, Atlanta, GA, 2004.)

this by a combination of both behavioral adjustments and physiological adaptations. The results of this research were incorporated in a revision to ASHRAE standard 55. This was implemented in the 2000 revision of ASHRAE comfort standard 95 and is valid only when the mean monthly outdoor temperature is between 10°C (50°F) and 33.5°C (92.3°F) (Figure 5.16). This standard, which was originally based solely on the PMV model, now has an optional method for determining acceptable thermal conditions in naturally conditioned spaces. *ASHRAE standard 55* (2010) states that occupants' thermal responses in naturally conditioned spaces depend in part on the outdoor climate and may differ from thermal responses in buildings with centralized air-conditioning systems. This is due to differences in recent thermal experiences, changes in clothing, availability of control options, and shifts in occupant expectations.

The method applies only to spaces without air conditioning and with operable windows that open to the outdoors. Mechanical ventilation with unconditioned air may be used, but opening and

closing of windows must be the primary means of regulating conditions in the space. The space may have a heating system, but this optional method does not apply when the heating system is in operation. The occupants must be engaged in near-sedentary activities with metabolic rates from 1.0 to 1.3 mets. The users of a space can undertake three types of adaptive processes to achieve thermal comfort: (1) behavioral (e.g., clothing, body movements, or adjustments such as windows to modify the body's heat balance); (2) physiological (e.g., vasodilation, vasoconstriction, shivering, and sweating); and (3) psychological adaptations (e.g., thermal perceptions and expectations). Because of these adaptations, neither humidity nor air speed limits need to be considered in this model. However, with high humidity (i.e., above 70%) it is difficult to believe that temperatures in the upper portion of the chart (i.e., above 29°C) will be neutral temperatures.

The neutrality temperature in this model can be calculated using the following correlation:

$$T_n = 18.9 + 0.255\,ET_{\text{out}} \tag{5.4}$$

where:

ET_{out} is the outdoor average effective temperature that accounts for humidity

T_n is the neutrality temperature

The implementation of the adaptive model in the ASHRAE comfort standard is important because it accepts that naturally ventilated buildings, in which the occupants have more control over their thermal environment, have a larger comfort zone. A larger comfort zone in naturally ventilated buildings promotes the implementation of passive cooling strategies in buildings, highlighting the role of the user in controlling the thermal environment.

ASHRAE Standard 55-2004 provides an option for adaptive comfort derived from neutralities and temperature preferences in naturally ventilated spaces as a function of prevailing outdoor temperature. In this standard there is a chart indicating the temperature ranges that correspond with thermal acceptability ratings of 90% and 80% (Figure 5.16). The value of $T_{a(\text{out})}$ is the average outdoor monthly air temperature calculated using the arithmetic average of the mean monthly minimum and maximum daily air temperatures for the month in question. The preferred temperature inside a naturally ventilated building increases by approximately 1 degree for every 3 degree increase in mean monthly outdoor air temperature (Brager and de Dear, 2000). The linear equation for the optimum comfort model described by Figure 5.16 and its acceptability limits, collectively known as the Adaptive Comfort Standard (ACS), can be written as

$$T_n = 0.31 \times T_{\text{ave}} + 17.5 \tag{5.5}$$

where:

T_{ave} is the monthly mean outdoor air temperature

T_n is the neutrality temperature

The European standard for naturally ventilated buildings (EN15251) now also incorporates a version of an adaptive method developed by Nicol and Humphreys (2010). The equation for thermal comfort for buildings in the free-running mode (Annex A2) in European Standard EN15251 rests on the data collected in the EU project Smart Controls and Thermal Comfort (SCATs). The equation proposed by Nicol and Humphreys is

$$T_n = 0.33 \times T_{\text{ave}} + 18.8 \tag{5.6}$$

where:

T_{ave} is the monthly mean outdoor air temperature

T_n is the neutrality temperature

The equation and charts proposed for this standard are similar, but not identical, to those proposed by the ASHRAE standard. The differences between the two equations are probably a result of several differences in the research. The databases are different because ASHRAE 55-2004 uses the data from the ASHRAE world database of field experiments collected by de Dear and Brager (1998), while EN1521 uses the data from the more recent European SCATs project. The ASHRAE adaptive standard applies only to naturally ventilated buildings, whereas the EN15251 applies to any building in free-running mode, thus including more buildings. The derivation of the neutral temperature is different, and the outdoor temperature is defined differently; ASHRAE is defined in terms of the monthly mean outdoor temperature, while EN15251 uses a running average.

It is now generally accepted that people in free-running buildings may also make various adjustments to themselves and their surroundings to reduce physiological strain. This adaptive approach is a behavioral approach because it assumes that people will respond to variations by adjusting to them through conscious actions related to their bodies or their environments. Bodily adjustments are primarily connected to clothing, posture, activity schedules, and activity levels, and environmental adjustments are connected to ventilation, air movement, and local temperature. They might also include unconscious long-term changes to physiological set points for control of shivering, skin blood flow, and sweating.

5.5 THE PERCEPTION OF COMFORT

Traditional comfort standards aim to achieve a thermal "steady state" across time and a thermal equilibrium across space (Fitch, 1947). There is an underlying assumption that the best thermal environment never needs to be noticed and that environmental control systems are directed to produce standard comfort conditions. However, this is not necessarily true; changes in the perception of the thermal environment help us connect with the daily rhythms of the environment that surrounds us. Furthermore, as climate becomes more erratic and extreme, it will become more challenging to achieve stable comfortable environments without substantially increasing energy use and emissions.

It is a fact that thermal comfort has a physiological basis and is affected by the heat balance of the human body and the four environmental and personal variables discussed in this chapter. However, comfort zones should not be static and narrow. Thermal comfort is affected by other variables. The temperature that most people find comfortable in naturally ventilated buildings, and maybe in all passive buildings, will vary with the outdoor temperature as people change their behavior to adapt to the changes in outdoor temperature, sometimes even anticipating it, reinforcing our connection with the environment that surrounds us. This process establishes a strong connection with the outdoor environment and nature's rhythms. Furthermore, the nature of this adaptive process is very complex, and other factors probably have not been quantified yet and also affect thermal comfort. Psychological, social, and cultural factors most likely have more influence than is currently accepted. For example, in the same developing country, people who live, work, and travel in air-conditioned spaces will probably have a different comfort zone from others who live, work, and travel in unconditioned spaces.

The fact that adaptive comfort is gaining importance and is being incorporated into codes is significant because buildings with wider comfort bands have better opportunities to implement passive heating or cooling systems. The implementation of adaptive comfort as part of a thermal comfort standard is a step in the right direction. However, more should be done. Kwok and Rajkovich (2010) suggest a mesocomfort zone that exists between the "optimum" thermal comfort conditions specified by static models and thermal environmental conditions that produce involuntary responses and that would provide opportunities for adaptation. The size of this zone would be expected to be proportional to the adaptive capacity of a space when combined with the opportunities afforded to the occupant. Some of these opportunities are directly linked to the building design.

If the comfort zone becomes a sliding band that moves with the seasons and building users have a more active role in maintaining comfort inside a building, it will be easier to design comfortable

low-carbon buildings than if fixed, narrow thermal comfort bands with no user control are used. If we understand that users have more potential to participate in the control of their environment and that a building can provide thermal controls through other means than the simply mechanical, we will be closer to the creation of low-carbon, climate-responsive, living buildings and farther from the sealed, inefficient, carbon-emitting buildings of today.

5.6 DESIGNING FOR COMFORT

Understanding the variables that affect thermal comfort and how these interact is important to effectively design thermally comfortable spaces. Thermal comfort can be improved and predicted by affecting the environmental variables that affect thermal comfort: temperature, air velocity, relative humidity, and solar radiation. This is true in indoor and outdoor environments.

In indoor environments it is possible to modify temperature and relative humidity with mechanical systems. If building gains are high in a warm and humid climate, the mechanical system can cool and dehumidify the space while the building envelope contains it and keeps it inside the building. Air velocity is usually kept low and radiant effects are implemented only in some systems.

The same four variables also have an effect on thermal comfort in outdoor environments, which must also include design features that allow them to be used under many weather conditions. However, there is no tight envelop that contains the air to work with. For example, if the air in an outdoor space is cooled, it will be spilled and mixed very quickly with warmer air and the cooling effect is lost. It is usually easier to modify other environmental variables that also affect thermal comfort such as solar radiation and air velocity. A very common strategy, for example, is to add shade in warm climates to block the radiant effect of the sun or to block the wind in cold climates.

A large portion of the world's population lives in cities, and millions of these live in hot and humid climates. There has not been an effective solution to achieve comfort in outdoor spaces, which have been limited to provide shade and air movement. This lack of outdoor comfort affects the quality of life, health, and productivity of the people who live in these cities.

The following two examples show proposals to improve thermal comfort in a hot and dry climate and a warm and humid climate.

5.6.1 Improving Outdoor Thermal Comfort in a Hot and Dry Climate

For a mixed use project in the Middle East that included an important series of outdoor spaces, an important goal was to improve thermal comfort over all outdoor environments, increasing the comfort and the number of hours the outdoor space was used.

The climate is analyzed with special emphasis on the variables that affect thermal comfort (wind, temperature, solar radiation, and RH). Massing proposals were developed and insolation studies of the outdoor spaces were performed for the summer and winter to estimate the effect of solar radiation on thermal comfort. The winter is mild so emphasis was placed on summer analysis, from May 1 to October 31, from 8 a.m. to 6 p.m Surfaces that receive more solar radiation during the summer will be more uncomfortable. Critical areas are determined and solutions proposed and compared with average values (lower average values were better).

Due to the difficult summer conditions, in addition to shade, a network of "oases" where active measures provided extra cooling during hot times of day was proposed. In these oases the operative temperature would be lowered by combining evaporative cooling and radiant cooling. Climate analysis indicated the feasibility of evaporative cooling due to the higher wet-bulb temperature depression. Figure 5.17 shows hours in red as the critical, most uncomfortable hours of the year, and include all summer days until 6 p.m Light blue indicates hours in which evaporative cooling will perform better, cooling the air by at least 10°C. Overlaying these two and shown in black are "critical hours" that can be made more comfortable with evaporative cooling. This indicates an area of maximum performance, when they are needed most, in the summer afternoon into the evening.

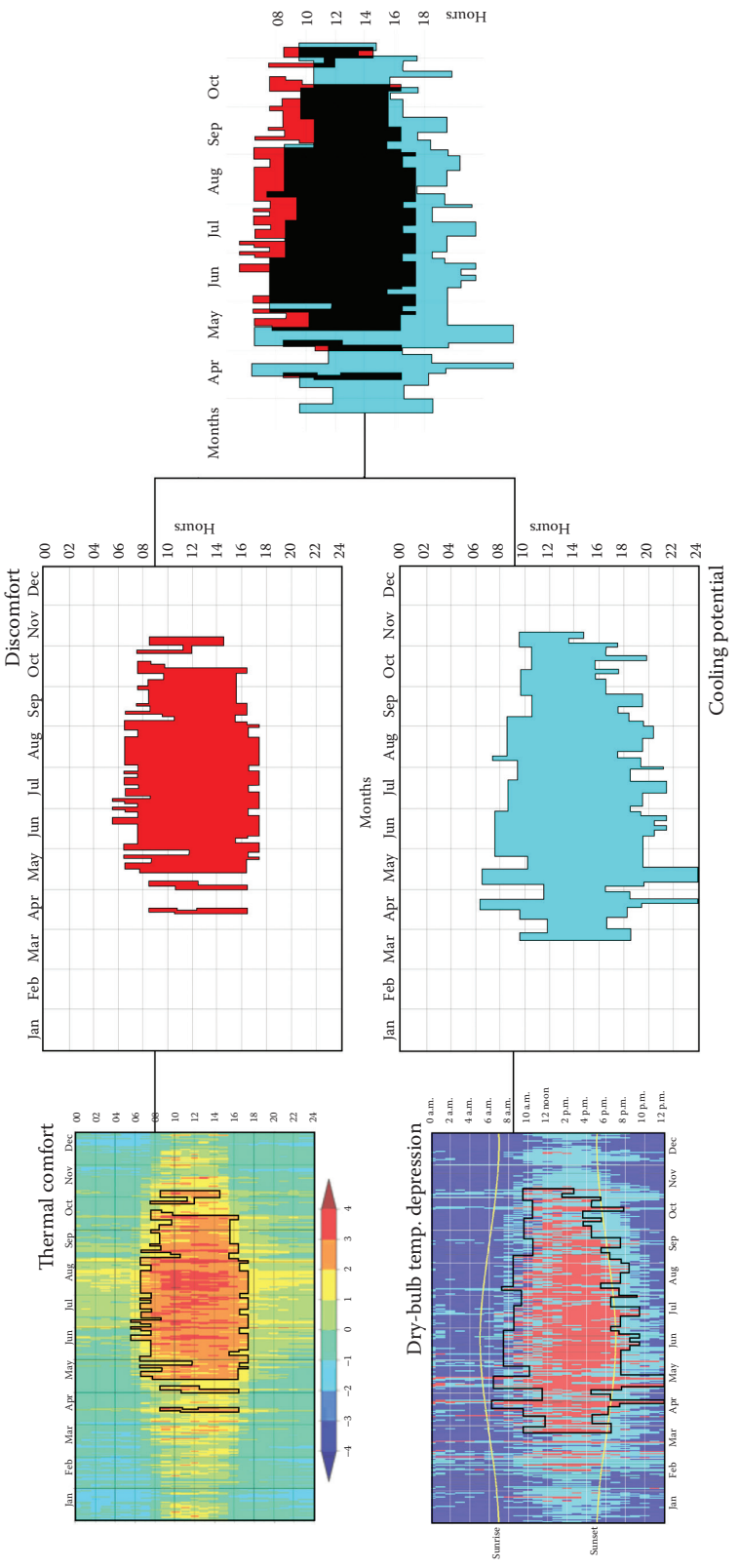


FIGURE 5.17 Evaporative cooling potential. (Courtesy of CallisonRTKL.)

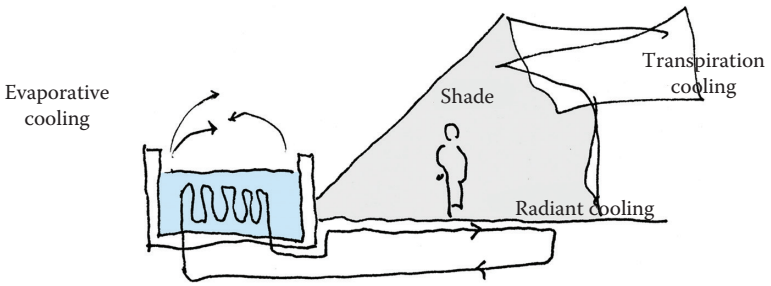


FIGURE 5.18 Concept for evaporative and radiant cooling. (Courtesy CallisonRTKL.)

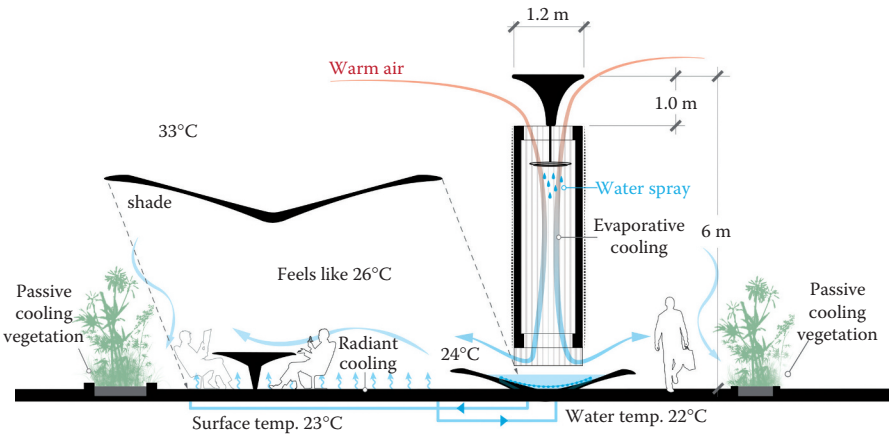


FIGURE 5.19 Concept for localized outdoor comfort stations (LOCS). (Courtesy CallisonRTKL.)

The initial concept included a fountain that cools the air around it through evaporative cooling. In addition, there are radiant pipes in the fountain and embedded in the pavement around it. The water from the fountain is pumped through the shaded floor, cooling it and improving the thermal comfort of the people above. The warm water is returned to the fountain where it is cooled by the sprinkling process and the heat is transferred to the air around the fountain (Figure 5.18). This concept was further developed and refined into what we called localized outdoor comfort stations (LOCS) that include a combination of strategies such as evaporative cooling, shading, and wind control to effectively improve comfort by lowering the perceived temperature. Figure 5.19 conceptually shows the LOCS components. Each of these could be selected from a kit of parts with multiple components that include evaporative cooling, shading, and wind control.

5.6.2 Improving Outdoor Thermal Comfort in a Hot and Humid Climate

Traditional cooling strategies in a hot and humid climate are very limited, consisting of shade and natural ventilation. A team from CallisonRTKL (J. E. Chung, P. La Roche, A Ponce, N Gemigniani) proposed a concept, named after Xylem, to provide additional outdoor thermal comfort while mitigating the heat island effect (Figure 5.20).

The Xylem improves outdoor thermal comfort by implementing a vegetated roof and water circulation for radiant cooling in addition to shading and natural ventilation. One of the unique elements of the Xylem pad is a planter pad at the top with the presence of a large thermal capacity in a green roof. The green roof concept was further developed based on previous green roof research

FIGURE 5.20 A single Xylem. (Courtesy of CallisonRTKL.)

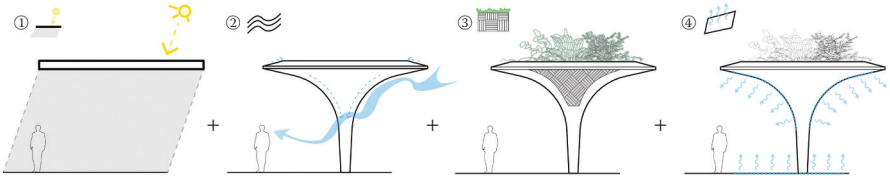
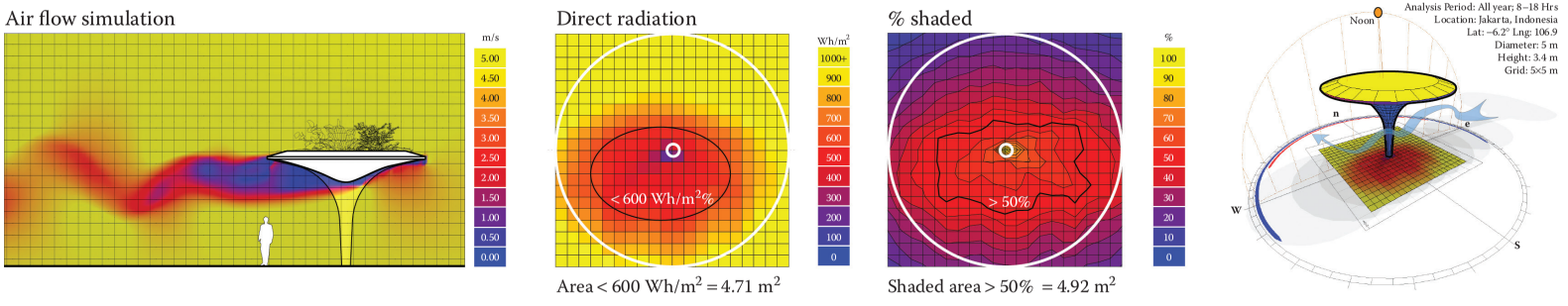


FIGURE 5.21 Xylem cooling strategies. (Courtesy of CallisonRTKL.)

(La Roche, 2009, 2013; La Roche and Berardi 2014; Yeom and La Roche 2016) so that it could actually be used for cooling. Even though it has been developed for hot and humid climates, it can also be implemented in hot and dry climates. The Xylem improves outdoor thermal comfort by implementing four outdoor cooling strategies: a large canopy for shading, promoting natural ventilation, a vegetated roof for thermal mass, and water circulation for radiant cooling (Figure 5.21). The form of the Xylem maximizes shade by its large diameter at the top while its curvature and slender stem provides for air flow at the bottom (Figure 5.22).

The components and assemblies of the Xylem pods are based on performance and aesthetic qualities, as well as a consideration to the currently available technologies in manufacturing and fabrication. The form has been designed to capture air flow from above and push it to the occupant's level, while also providing shade. Liquid-filled tubes embedded in the soil of the planting material are cooled to a lower temperature than the air temperature; the water in these tubes then cools panels at the occupant level and in the ground around the center of the pod, cooling the person above the ground or close to the panels by radiation (Figures 5.23 and 5.24). An air space between the earth and the panels also helps to insulate the earth while providing an opportunity to also provide cool air at the lower level (Figures 5.25 and 5.26). Photovoltaic panels integrated in the Xylem at the top provide electricity to the pumps that circulate the water. The original design proposes water flowing through capillary mats; however, it is possible to substitute the mats by small tubes, and in fact it is also possible to substitute many of the components with other locally available materials as long as the energy flows are kept as proposed.

As cities replace vegetation with paved surfaces, "islands" of higher temperatures increase energy consumption in buildings, emissions of GHG, and pollutants while compromising human health. The Xylem incorporates multiple strategies to reduce the heat island effect; the vegetation above the Xylem shades its surface while evaporation from these vegetated surfaces also cools the air by using heat from the air to evaporate water; the Xylem itself shades the ground below reducing heat absorption. According to the Environmental Protection Agency (EPA) evapotranspiration, alone

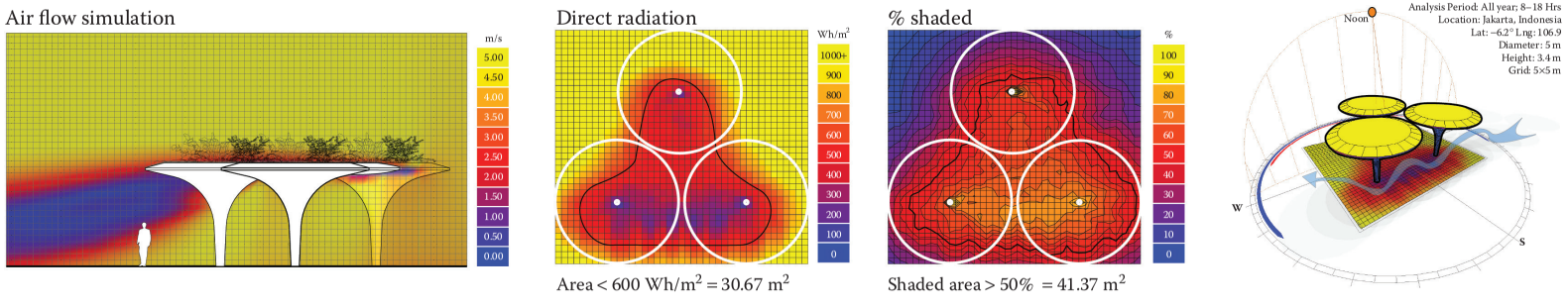


Area < 600 Wh/m^2 = 4.71 m^2

Shaded area > 50% = 4.92 m^2

Microscale

The single pod form is optimized for maximum shade and air movement at the Occupant level. Just as a tree provides shade and allows breezes to move below its canopy, Xylem replicates these effects



Area < 600 Wh/m^2 = 30.67 m^2

Shaded area > 50% = 41.37 m^2

Macroscale

Just as a cluster of trees improves the amount of shade on a given area, clusters of Xylem exponentially increase their cooling potential, furthering reducing the heat island effect and increasing thermal comfort.

FIGURE 5.22 Solar and wind analysis of xylem. (Courtesy of CallisonRTKL.)

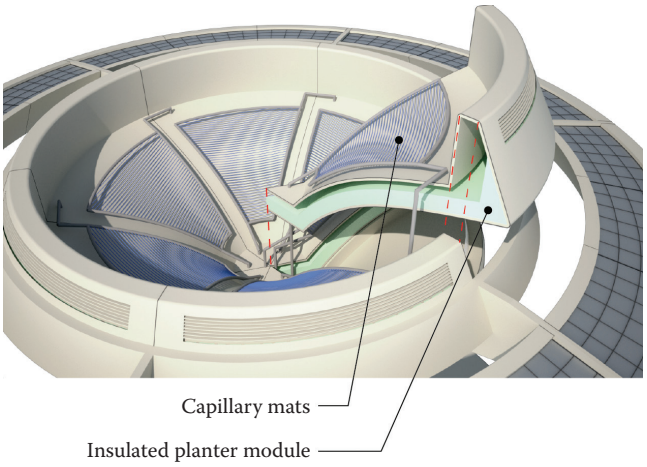


FIGURE 5.23 Capillary mats inside the green roof. (Courtesy of CallisonRTKL.)

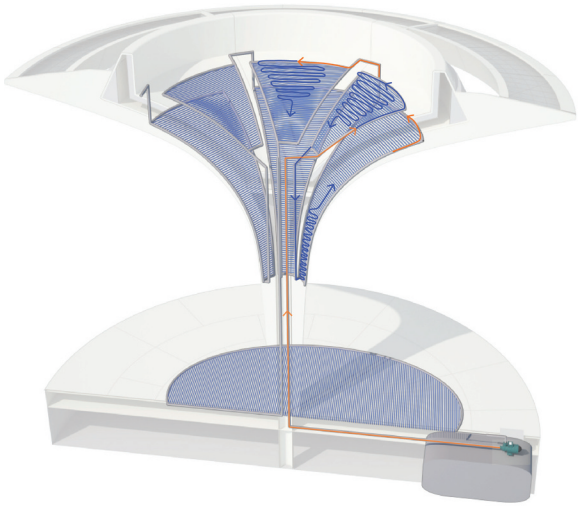


FIGURE 5.24 Pipe water diagram in the xylem. (Courtesy of CallisonRTKL.)

wor in combination with shading, can help reduce peak summer temperatures by 1°C–5°C. When combined in canopies they can lower local temperatures by an additional 2°C and reduce peak loads in the summer and overall energy consumption. Kurn et al. (1994) estimated that near-surface air temperatures over vegetated areas is 1°C–2°C lower than background air temperatures. We estimate that vegetation may lower urban temperatures by 1°C, while the establishment of vegetative canopies may lower local temperatures by an additional 2°C. An increase in vegetation in residential neighborhoods may reduce peak loads in the Los Angeles area by 0.3 GW, and reduce energy consumption by 0.2 BkWh/year, saving $20 million annually. Large additional savings would result from regional cooling.

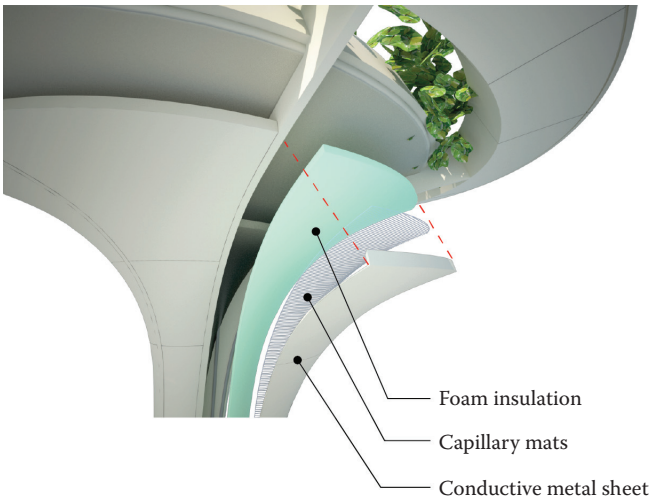


FIGURE 5.25 Capillary cooling. (Courtesy of CallisonRTKL.)

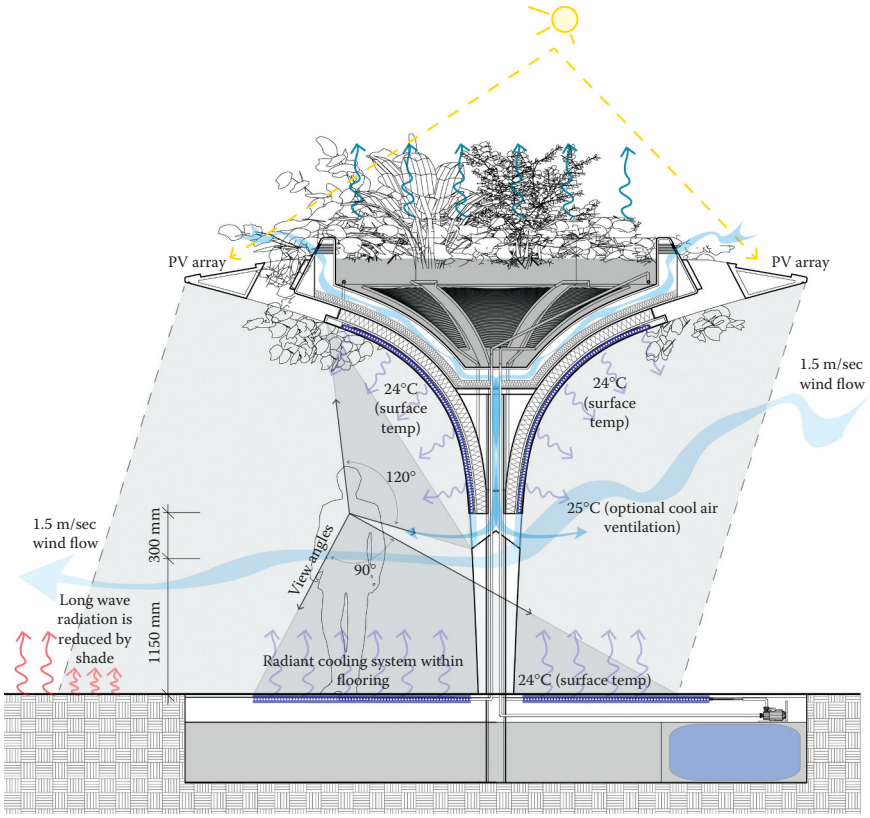


FIGURE 5.26 Xylem and thermal comfort. (Courtesy of CallisonRTKL.)

FIGURE 5.27 Cooling effect increases when Xylem is combined. (Courtesy of CallisonRTKL.)

FIGURE 5.28 Combined Xylem can be used for multiple applications. (Courtesy of CallisonRTKL.)

While a single Xylem pod provides thermal comfort at the user level, the Xylem also seeks to reduce the heat island effect on a larger, urban scale by creating clustered communities of comfortable environments that reduce the effects of direct solar gain and increase each Xylem's cooling potential. When combined as a community of clusters, the Xylem pods reduce the heat island effect, improving both outdoor and indoor conditions (Figures 5.27 and 5.28).

The Xylem can be used and adapted for multiple outdoor programs in different locations and cultures including plazas, markets, playgrounds, beaches, outdoor malls, and community centers. Even though it was designed as a solution for difficult hot and humid climates, it can also be used in hot and dry climates with larger daily swings or in temperate climates with hot summers. This prototype can be further developed to include additional features such as rainwater harvesting and storm mitigation. The Xylem is flexible.

6 Climate and Architecture

6.1 CLIMATE

Differences in climate are caused by the differential solar heat input and the almost uniform heat emission over the Earth's surface. Equatorial regions receive much greater energy than areas near the pole, and this differential, together with, for example, the rotation of the Earth and the presence of land or water masses and mountain ranges, is the main driving force of atmospheric phenomena.

Weather is generally assumed to be the set of atmospheric conditions prevailing at a given place and time, and *climate*, from the ancient word *clime*, is usually thought of as the integration in time of weather conditions, characteristic of a certain geographical location (Docherty and Szokolay, 1999).

6.2 CLIMATE AND ARCHITECTURE

The amount of energy used in a building is a direct result of the interactions among the external environment, the building's program, and the building's form. Buildings should be able to regulate outdoor conditions and to harness available energy to achieve internal comfort with minimum emissions.

The climate where the building is located can be understood through the analysis of data, which are collected in meteorological stations and are published in summary form usually. Examples of these data include the following:

Dry-bulb temperature
Relative and absolute humidity
Air movement, measured as wind speed and direction
Precipitation, measured as the total amount of rain, hail, snow, or dew in millimeters per unit time (e.g., day, month, and year)
Cloud cover based on visual observation and expressed as a fraction of the sky hemisphere covered by clouds (tenths, or octas = eighths)
Sunshine duration, the period of clear sunshine (when a sharp shadow is cast), measured by a sunshine recorder that burns a trace on a paper strip and expressed as hours per day or month
Solar radiation, measured by a pyranometer on an unobstructed horizontal surface, usually recorded as the continuously varying irradiance (W/m^2)

The most important climate variables in building design are those that directly affect thermal comfort: temperature, humidity, solar radiation, and air movement. Precipitation data are helpful in designing drainage systems and slopes; even though these data do not directly affect building energy use, they are correlated with other climate parameters that affect building energy use: solar radiation, cloud cover, relative humidity, diurnal temperature swing, and wet- and dry-bulb design temperatures.

Furthermore, climate variables also affect the building design and emissions in different ways. Temperature affects heating and cooling loads; moisture content of the air also affects cooling loads and in some degree heating loads; radiation affects heating, cooling, daylighting, and active systems such as domestic solar hot water and photovoltaic systems; wind affects airflow inside buildings and renewable systems such as windmills; precipitation affects water use; cloud cover affects heating, cooling, daylighting, and photovoltaics. Figure 6.1 shows the relationship between climate variables and some building properties.

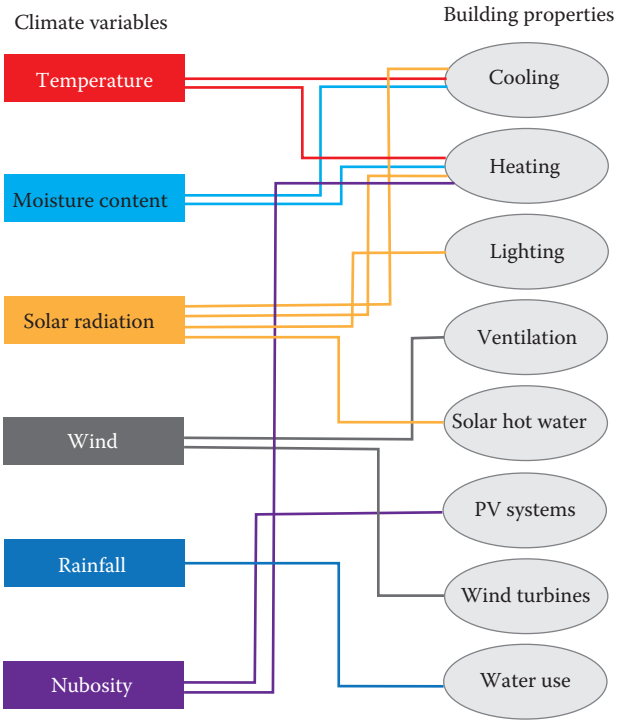


FIGURE 6.1 Effects of climate variables on building design and emissions.

To study year-round building performance, annual weather data are required. A minimum amount of data is necessary for an adequate design:

1. Temperature: monthly mean of daily maxima and daily minima (°C or °F)
2. Humidity: minimum and maximum mean relative humidity (%)
3. Solar radiation: monthly mean daily total (in MJ/m^2 or Wh/m^2)
4. Sunshine: (%)
5. Wind: prevailing wind speed (m/s or mph) and direction
6. Rainfall: monthly total (in millimeters or inches)

For an easier understanding of the data, the raw weather data from the meteorological stations are usually presented in tabular or graph form. Some design handbooks and standards such as American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) also provide general climatic data for building design and manual load calculations.

The degree day is a unit of measurement that indicates the heating or cooling demand in a building and helps to define the severity of the climate. There are two types of degree days: heating degree days (HDDs) and cooling degree days (CDDs). A HDD indicates the energy required to heat the building and is defined relative to a base temperature, which is the outside temperature above which the building does not need any heating. This base temperature is affected by building design characteristics such as the level of insulation and size and position of the openings, but also by other factors such as the amount of solar radiation falling on the building or the amount of heat generated by people or appliances inside the building. A tighter well-insulated building will have a lower base temperature than a leaky noninsulated building. In the United States, HDD tables have usually been provided with base temperatures of 18.3°C (65°F) or 15.5°C (60°F). A HDD can be calculated at any time interval, and shorter intervals provide more precision. However, it is usually calculated

using average daily values, which are then added to determine the yearly total. For example, if the reference temperature is 18.3°C (65°F) and the average outdoor temperature for a given day is 10°C (15°F), then the HDD for that day is 8.3°C. This would be done for every day of the year to determine the yearly total. A CDD indicates the amount of energy required to cool the building and is defined relative to a base temperature, which is the outside temperature above which the building needs to be cooled. CDDs are usually calculated from the same base temperature as HDDs; thus whenever the outside temperature is above this base temperature, cooling will be required, and whenever it is below, heating will be required. With the advent of energy simulation tools and more precise methods to determine energy use in a building, the use of HDD and CDD is declining; however, it provides an easy way to visualize the severity of a winter or a climate in a given location.

The development and generalized use of detailed building energy simulation programs has generated the need for hourly data for whole years. In a short time, hourly data have become the standard for climate analysis and energy simulation. Most data set systems construct a composite year's data by selecting periods from actual data over many years of recording. These types of data have different names depending on the country: in the United States, typical meteorological year (TMY) and EnergyPlus weather files (EPW); in the United Kingdom, the Chartered Institution of Building Services Engineers (CIBSE); in China, the Chinese Standard Weather Data (CSWD); in Australia, the representative meteorological year (RMY); in New Zealand, the New Zealand Data (NiWA); and in Spain, the Spanish Weather for Energy Calculations (SWEC). These files are powerful because they provide hourly data for the whole year; however, because of the process by which they are generated, the values in the files might not accurately reflect conditions in a given location.

Precipitation, terrain, vegetation, degree of solar exposure, wind patterns, the presence of water bodies, geology, and the influences of buildings or other built forms on or near the site can create unique, site-specific, climatic conditions that could be very different from those of the closest weather station and thus can considerably affect the building and its design. The architect should try to determine microclimate effects by collecting data on-site through low-cost weather stations or by trying to determine the microclimatic effects with available data.

Climate graphs and charts can now be created from yearly data using climate analysis software. Figures 6.2 and 6.3 show climate data generated with two widely used climate analysis tools:

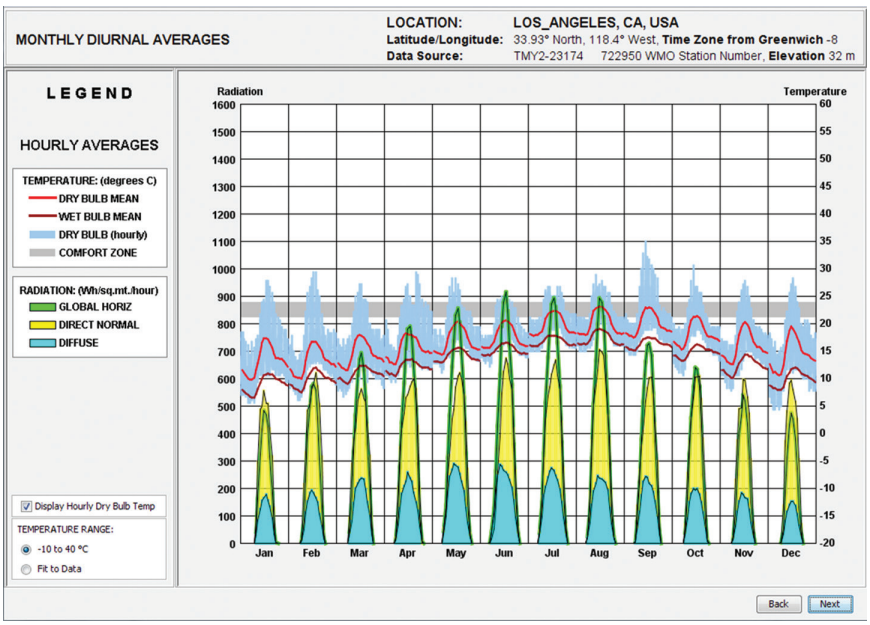


FIGURE 6.2 Monthly climate data plotted with Climate Consultant.

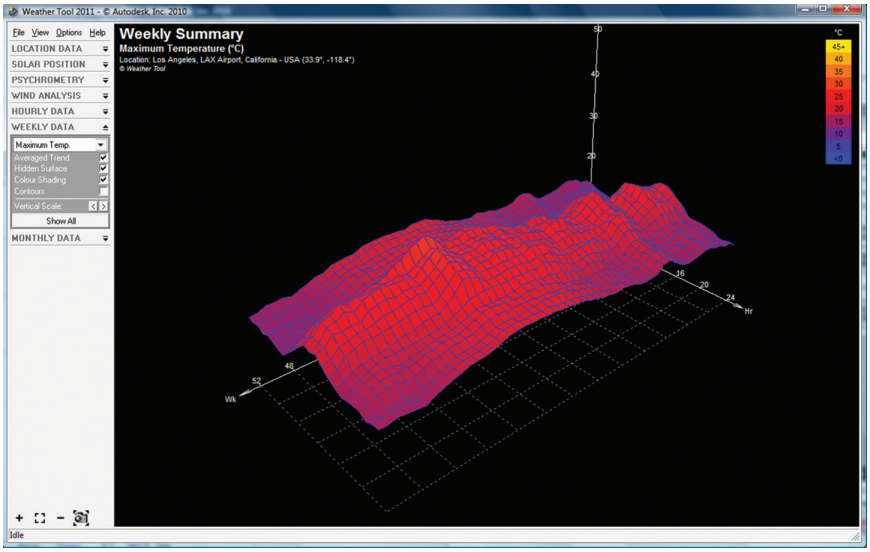


FIGURE 6.3 Weekly temperature data plotted with Ecotect's Weather Tool.

Climate Consultant, developed at the University of California, Los Angeles (UCLA) by Murray Milne and Robin Liggett, and the Weather Tool, now part of Ecotect, which is not available any more. These charts select appropriate information from the weather files and make it possible to understand the otherwise illegible yearly weather files. Figure 6.2 shows monthly diurnal averages of climate data for Los Angeles generated with Climate Consultant. It includes monthly mean and hourly values of dry-bulb temperature, mean wet-bulb temperature, global direct radiation, and diffuse solar radiation. The Weather Tool inside Ecotect can also show data in this form and can generate a weekly summary of the different variables. Figure 6.3 illustrates the weekly summary for maximum temperature using the same weather file for Los Angeles during the 24 hours and 52 weeks of the year.

6.3 CLIMATE ZONES

There are many climate classification systems, most of them based on vegetation types or amounts of precipitation. In 1884 Köppen proposed a climate classification system based on the concept that native vegetation provides the best way to define climate types. Köppen (1918) revised this classification system several times including one with Geiger, which is why it is sometimes called the Köppen-Geiger system. This system is still in use and consists of several climate groups subdivided into climate types and subtypes. Climate zone boundaries are selected according to the vegetation distribution, and then include quantitative definitions based on temperature and precipitation indices with their seasonality distribution. This classification scheme divides the climates into five main groups and several types and subtypes, and uses two- and three-letter symbols to designate the climate types.

Even though Köppen's climate classification system is the most widely used all over the world, it is not very useful for architectural purposes because it does not directly provide the information necessary to design a climate-responsive building. A climate classification system based on the relationship between the climate variables and human thermal comfort would be more useful than a system based on vegetation or precipitation. Comfort depends on the dissipation of the body's metabolic heat production by radiation, convection, evaporation, and conduction; discomfort will occur when there is insufficient or too much dissipation. As discussed in Chapter 3, the amount of heat

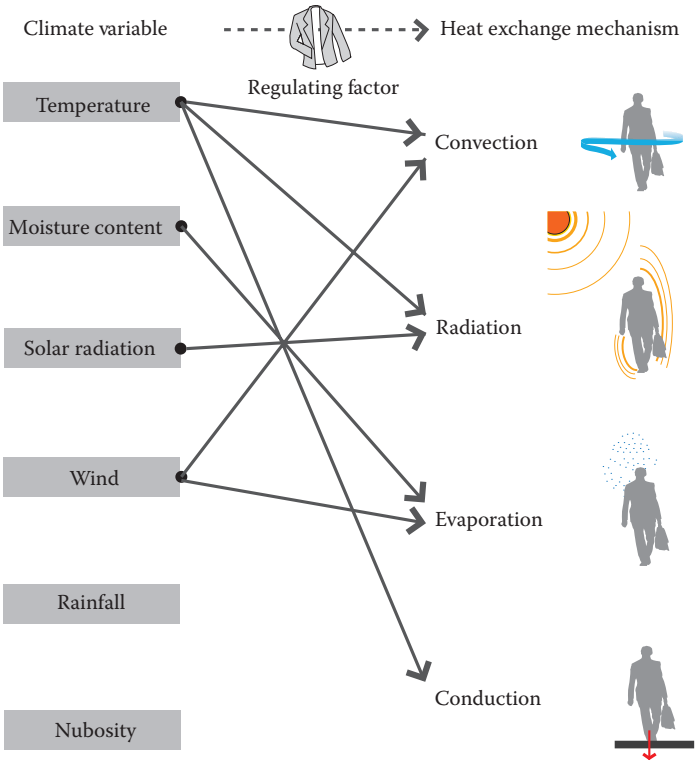


FIGURE 6.4 Effects of climate variables on heat transfer mechanisms.

dissipated through various mechanisms varies, but, in still air and in temperatures close to 20°C, without conductive contact the heat dissipation will be about 45% by radiation, 30% by convection, and 25% by evaporation. This heat transfer exchange is affected by climate variables in different ways. The convective exchange is affected by the dry-bulb temperature and air velocity. The radiant exchange depends on the thermal relationship between the skin and the surfaces around it. The temperature of the skin is relatively constant, but the temperature of the surrounding surfaces is affected by the temperature of the air and the intensity of solar radiation hitting these surfaces. The moisture content of the air affects the rate of evaporation from the lungs and the rate of sweat evaporation, which is also affected by air velocity. Conductive exchanges are usually minimal, because they occur only when the human body is in contact with a surface and are affected by the air temperature and radiation on the body or the surfaces (Figure 6.4).

Using this classification based on the connection between the climate variables and thermal comfort, climates can be sorted into four types: cold, temperate, hot and dry, and hot and humid. This simple climate classification is easier to understand and more practical for architectural purposes than Köppen's classification and has been adopted by many authors (Moffat and Schiler, 1981; Achard and Gicquel, 1986). It is possible to determine the type of climate by the location of the hourly or monthly data points in the psychrometric chart. This will be discussed later in the chapter.

The main problem in a cold climate is the lack of heat (i.e., underheating), which causes excessive heat dissipation during all or most parts of the year. In a temperate climate the problem is excessive heat dissipation during the warmest months of the year and inadequate heat dissipation during the coolest months of the year. There is a seasonal variation between underheating and overheating, but neither of the seasons is very severe. A hot, dry (arid) climate is typified by large diurnal temperature swings and the main problem is overheating, with insufficient heat dissipation

from the body; however, the dryness of the air allows evaporative cooling to take place, which provides additional cooling opportunities for the body. Elevated temperature and radiation characterize these climates. In hot, humid climates, the air temperatures are lower than in hot, dry areas, but there is relatively little night drop, and the main problem is still overheating with conditions aggravated by high humidity, which limits the evaporative cooling effect. If these four climate types are compared with Köppen's classification, a type A climate would be hot and humid, type B would be hot and dry, type G would be temperate, and type H would be cold.

6.4 CLIMATE ZONES AND ENERGY CODES

Legislation is an important tool for change. Unfortunately, advances in legislation are slow and should move to improve performance and away from prescriptive requirements to performance-based requirements based on indicators such as yearly energy use or greenhouse gas (GHG) emissions per unit area per unit of time. To achieve this, designers must be better educated in the available mechanisms. Even if countries sign accords to reduce emissions, it is impossible to reach these goals if codes do not mandate improved performance that will reduce emissions in all areas.

In addition to the major humid, dry, and marine climate types, the divisions among climate zones for energy codes have mostly been developed based on thermal criteria. After the 1980s, climate data were widely available in many locations in the United States, and computer-processing power was cheaper. This led to a climate classification based on the agglomeration of similar sites using a statistical procedure called *hierarchical cluster analysis*. This type of analysis uses a distance metric that represents the degree of similarity or dissimilarity between observations in a data set. Cluster analysis has been discussed by several authors (e.g., Oliver, 1991) and has been used by some standards such as ASHRAE Standard 90.1.

In the United States, probably the most important energy code is the International Energy Conservation Code (IECC), which covers new construction, additions remodeling, window replacement, and building repairs. The first IECC climate zones were based only on heating degree days and did not account for cooling energy (Building Energy Codes Resource Center, 2010). On the newer 2009 IECC maps, the climate zones were developed from the analysis of 4775 National Oceanic and Atmospheric Administration (NOAA) weather sites. A climate classification system that provided quantitative definitions for three major climate types—humid, dry, and marine climates—was developed. The reasoning is that these major climate types are the most essential for building design because they are based on the most important variables in cooling and heating loads, such as wet-bulb temperature and variations in solar radiation and HDDs and CDDs.

These three climate types are divided in eight climate zones that are defined by county boundaries and thus have been adopted by many organizations and codes including ASHRAE 90.1, ASHRAE 90.2, ASHRAE's Advanced Energy Design Guide for Small Office Buildings, Building America (modified), and Energy Star. The eight climate zones are distributed in roughly horizontal bands, except for the Rocky Mountains, spread across the country from the hottest zone (1) occupying the southern tip of Florida to the coldest zone (8) covering the northern half of Alaska. Regular increments of HDDs and CDDs were selected that worked well climatologically, that facilitated the representation of current code requirements, and that enabled a substantial reduction in the number of zones (Figure 6.5).

California's Energy Efficiency Standards for Residential and Nonresidential Buildings were established in 1978 in response to a legislative mandate to reduce California's energy consumption and are probably the most stringent energy codes in the United States. According to the California Energy Commission (CEC), California's building efficiency standards (along with those for energy-efficient appliances) have saved more than $56 billion in electricity and natural gas costs since 1978,

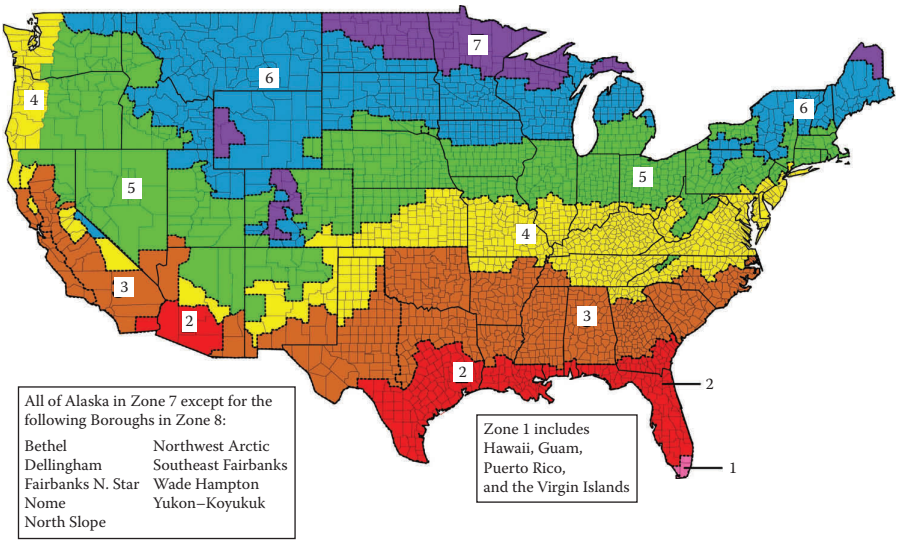


FIGURE 6.5 IECC climate zones in the United States.

and it is estimated that they will save an additional $23 billion by 2013. The standards are updated periodically to allow consideration and incorporation of new energy efficiency technologies and methods. The latest version of the standard went into effect in January 1, 2010. This code divides the state into 16 climate zones (Figure 6.6), each of which represents a geographic area with a similar energy budget, which is the maximum amount of energy that a building or portion of a building can be designed to consume per year (Title 24, Energy Efficiency Standards). The Energy Commission developed weather data for each climate zone by using unmodified weather year data for a representative city, which simplifies calculations but produces less precise numbers in some locations inside each climate zone. As with all climate zones, the borders sometimes are set by political rather than geographical boundaries, which makes enforcement easier but also generates problems with the precision of the budget.

The purpose of the European Union Energy Performance of Buildings Directive (EPBD) (2002/91/EC) is to promote the improvement of energy efficiency in buildings and to ensure convergence of standards across Europe. The law applies to both new projects and refurbishments and establishes a common basis for calculating energy performance, sets minimum standards, introduces energy performance certificates (EPCs), and requires heating and air-conditioning systems to be inspected regularly. The establishment of a common basis helps to unify all measuring systems so that the display energy certificates (DECs) or EPCs in smaller buildings can be implemented, which raises awareness of energy efficiency among users.

Many European building codes, such as the Danish 2008 building code, measure performance in total energy consumption in kWh/m^2/yr. The Danish code regulates new residential buildings at 70 kWh/m^2/yr in 2008 and down to 25 kWh/m^2/yr in 2020 and for nonresidential buildings from 95 kWh/m^2/yr in 2008 to 35 kWh/m^2/yr in 2020. In 2008 the United Kingdom introduced the Climate Change Act, which proposed to reduce CO_2 emissions by at least 80% from 1990 levels by 2050 and by at least 34% by 2020. This is a legally binding target that at the same time helps the United Kingdom achieve the reductions in emissions proposed in the 1997 Kyoto Protocol.

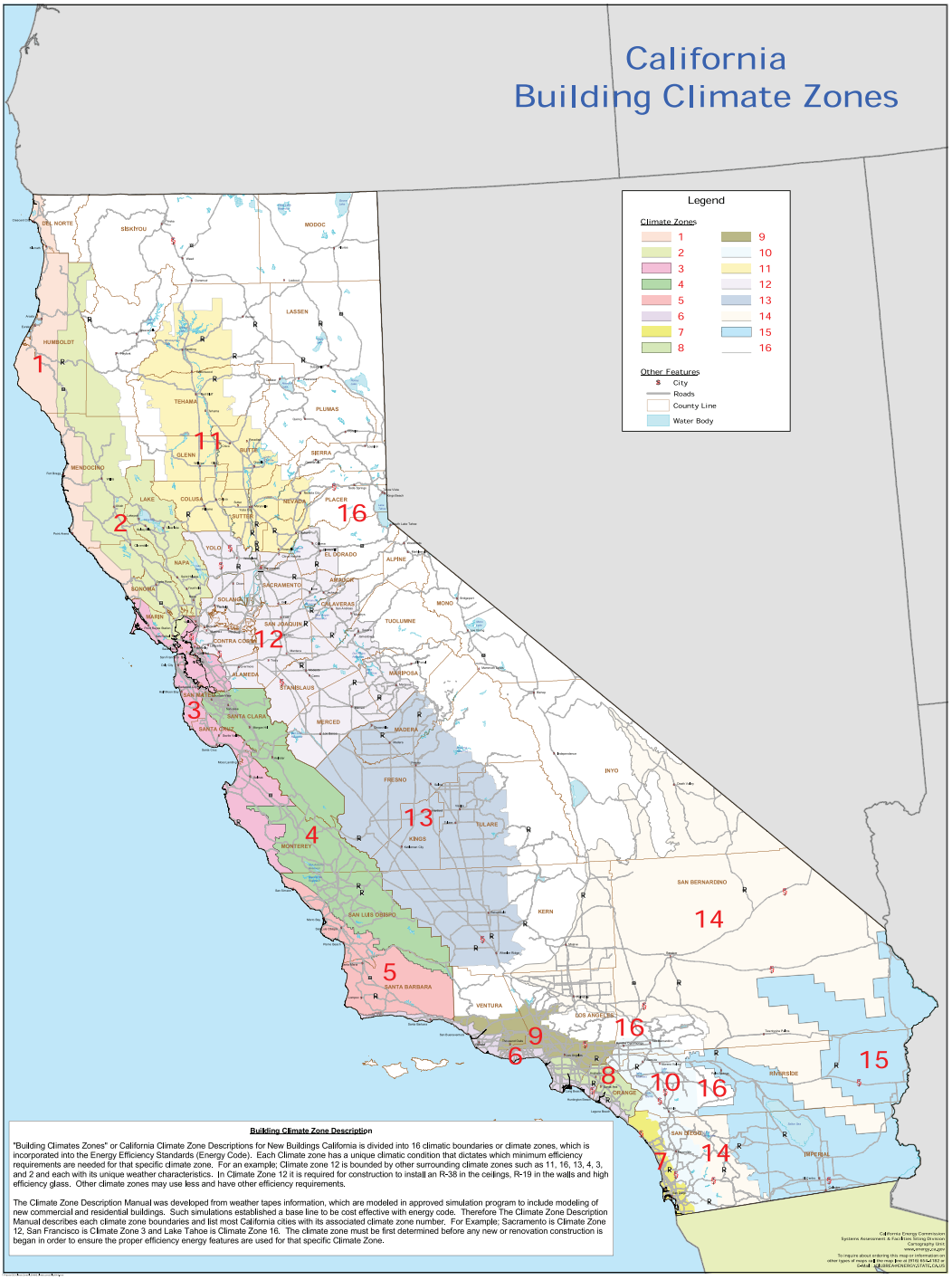


FIGURE 6.6 California Energy Efficiency Standards Title 24, Part 6 climate zones. (From California Energy Commission. With permission.)

6.5 CLIMATE ANALYSIS

Climate analysis uses information from the building site to determine the architectural design strategies that are most effective to harness natural forces through building design and to achieve thermal comfort. This process helps to produce buildings that respond better to local climate, that use less energy for heating and cooling, and that have a smaller carbon footprint. The first modern text that studied the relation between climate and buildings was probably Koenigsberger, Mahoney, and Evans's (1971) *Climate and House Design*, which proposed a relationship between climatic regions and the recommended bioclimatic design strategies to achieve thermal comfort in each of these.

The next step in the development of bioclimatic strategies was climate analysis methods that compared average climatic data for each month with the required comfort levels to determine the difference between the existing external conditions and the desired indoor conditions and to decide on the appropriate design strategies to achieve thermal comfort. This analysis was usually graphical and, until recently, was done by manually plotting average monthly values in the chart. Current climate analysis software can now analyze hundreds of data points in hourly weather files to generate information that is easier to understand and use (Figures 6.2 and 6.3).

6.5.1 Building Bioclimatic Chart

Bioclimatic design is used to identify potential building design strategies that use natural energy resources and minimize conventional energy usage to achieve thermal comfort. The building bioclimatic chart indicates design strategies that can be used for given outdoor combinations of temperature and relative humidity to achieve indoor thermal comfort, and it is called *bioclimatic* because it connects climate with human thermal comfort. The first BBCC to become generally accepted was by Olgyay, developed in 1963. In this chart, relative humidity is measured on the *x*-axis and temperature on the *y*-axis The comfort zone is plotted in the chart with a lower limit of the zone around 21°C (70°F) and an upper limit around 27°C (80°F), which gradually goes down until it connects with the lower limit of the comfort zone at a relative humidity of 90% (Figure 6.7). In addition to the comfort zone, this chart indicates wind and solar control strategies for different outdoor conditions expressed as combinations of dry-bulb temperature and relative humidity. Areas above the comfort zone are overheated and need ventilation, and areas below the comfort zone are overcooled and need solar radiation. Many versions of this chart have been developed and are still in use in different parts of the world; some of them indicate required air velocities or amounts of solar radiation to achieve comfort, which is probably the biggest strength of this chart.

An important problem with Olgyay's (1963) chart is that it does not account for differences between low-mass and high-mass buildings and assumes that the outdoor conditions, plotted on the graph, would be very close to the indoor conditions and can thus be used as guidelines for building design. Givoni (1998) states that this is only a reasonable approximation in lightweight naturally ventilated buildings in the summer of temperate or humid climates. But even in these buildings, especially at night, internal gains can generate winter indoor temperatures that can be significantly higher than outdoor temperatures, leading to an overestimation of the need for heating. In warm, dry regions, the daytime temperature inside a night-ventilated non-air-conditioned high-mass building can be several degrees lower than the outdoors. In this case, guidelines based on outdoor conditions would be inappropriate because the indoor temperature would be very different (lower) from the outdoor temperature, and guidelines based on outdoor values would recommend that the building be ventilated during the daytime and heated during the night, which would only overheat a high-mass building in the desert.

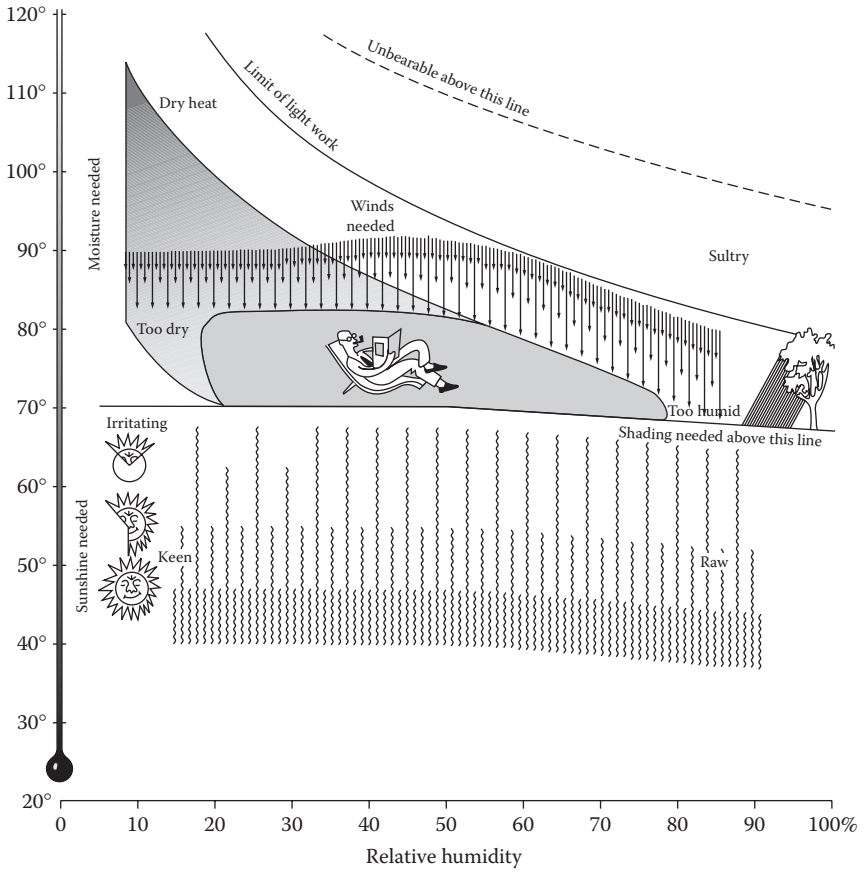


FIGURE 6.7 Olgyay's building bioclimatic chart. (From Olgyay, V., *Design with Climate, A Bioclimatic Approach to Architectural Regionalism*, Princeton University Press, Princeton, NJ, 1963. With permission.)

6.5.2 Givoni's Building Bioclimatic Chart

Givoni (1969) developed the building bioclimatic chart to address the problems associated with Olgyay's charts. This chart is based on the temperatures inside buildings (expected on the basis of experience or calculations) instead of the outdoor temperatures. Givoni used the psychrometric chart as the base of his BBCC for plotting the comfort zone and its extension (Figure 6.8) (Givoni, 1969). The psychrometric chart graphically represents the interrelation of air temperature and moisture content, and the BBCC, which is drawn in the psychrometric chart, becomes a useful design tool that indicates the boundaries of the outdoor climatic conditions within which various passive building design strategies can provide indoor comfort without the use of mechanical systems. In Givoni's original chart, several zones were listed together with the comfort zone. These indicate when different strategies can be used to achieve thermal comfort: natural ventilation, thermal mass, evaporative cooling, and air conditioning. The strategies are the same, but research has changed the demarcation of the zones. Milne and Givoni's (1979) chapter in *Energy Conservation through Building Design* added heating zones and further developed the method (Figure 6.9). Again, the cooling options included in the chart are daytime ventilation, high mass with or without nocturnal ventilation, direct evaporative cooling, and indirect evaporative cooling. Heating is addressed through passive solar heating. This chart and versions of this chart with different demarcations of the zones are used all over the world. Gonzalez,

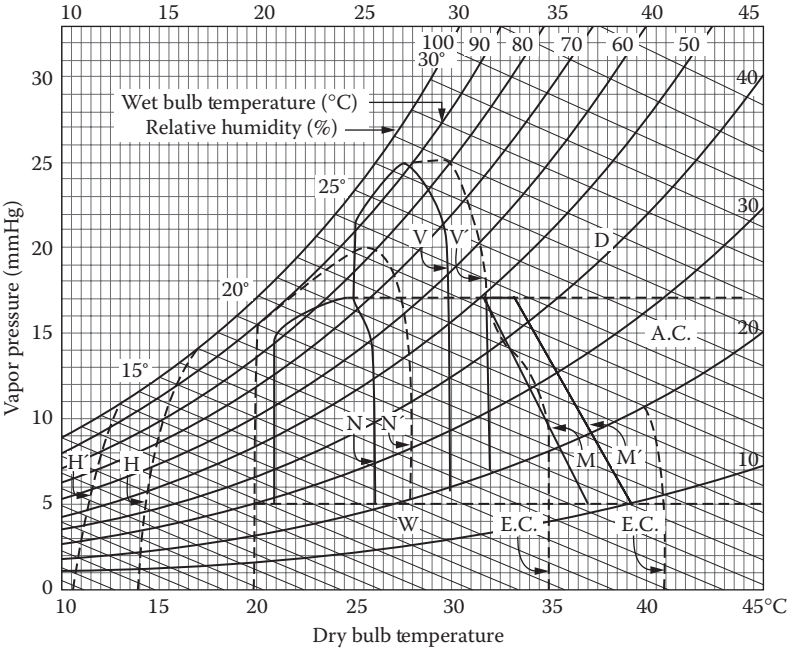


FIGURE 6.8 Givoni's building bioclimatic chart. (From Givoni, B., *Man Climate and Architecture*, London, Applied Science Publishers, 1969. With permission.)

Hinz, Oteiza, and Quiros (1986) compared several of these building bioclimatic charts to determine a new chart for hot and humid climates. These strategies are discussed in Chapter 10.

In 1998 Givoni revised the original chart based on updated research and proposed a revised buiding bioclimatic chart, which also included a distinction between developed and developing countries. In these charts he assumed that the upper limits of accepted temperature and humidity would be higher for persons living in developing countries and acclimatized to hot, humid conditions and extended the zone by which air movement could provide comfort by a couple of degrees to the right (Figure 6.10). To support this reasoning he used data obtained in comfort studies conducted in hot countries (Givoni, 1998). However, as stated earlier, social, cultural, and economic factors such as income level and work and home environments still play an important and unaccounted-for role that could generate different comfort zones among different social groups, even in the same location. For example, an individual living in a hot and humid climate and working and traveling in an air-conditioned environment would have a different comfort zone from an individual in the same city living, traveling, and working in non-air-conditioned environments. In this case, the zones for less developed and developed countries could be indicating zones for different groups inside countries instead of whole countries.

In the same fashion, Givoni also proposed a larger and warmer zone in which ventilation will help to achieve thermal comfort in hot developing countries (Figure 6.11).

Figure 6.12 is the author's version of Milne and Givoni's (1979) chart and will be used to explain passive solar concepts in Chapter 9. It follows Milne and Givoni's zones with two exceptions. First, the internal gains strategy is eliminated, because it is not really an architectural design strategy. It is more affected by the building program and, in many cases, is a liability instead of a strategy. Second, the thermal mass area that is traditionally to the right is integrated into one zone with thermal mass to the left and the right of the comfort zone. This indicates that the thermal mass can dampen outdoor swing when outdoor values are slightly toward either side of the comfort zone

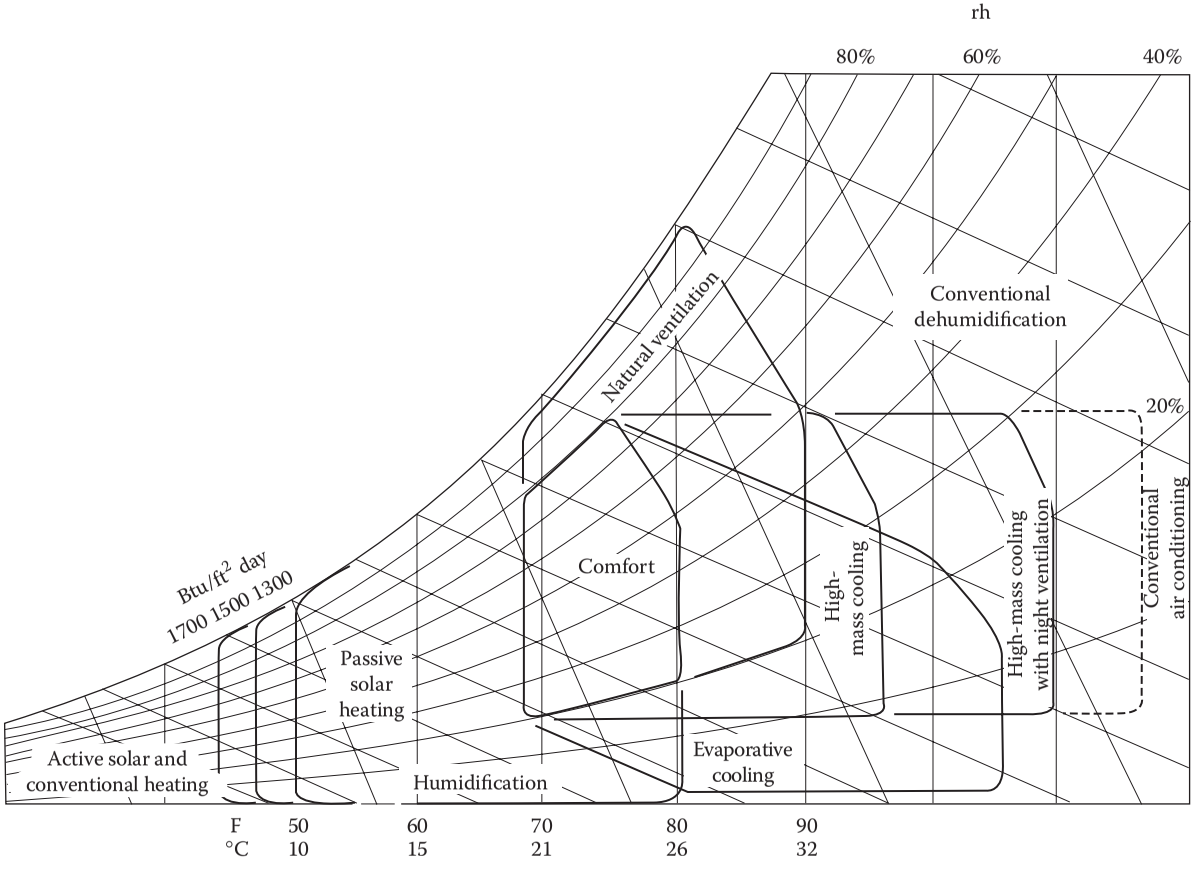


FIGURE 6.9 Milne and Givoni's revised building bioclimatic chart. (From Milne, M. and Givoni, B., in *Energy Conservation through Building Design*, D. Watson (ed.), New York, McGraw-Hill, 96–113, 1979. With permission.)

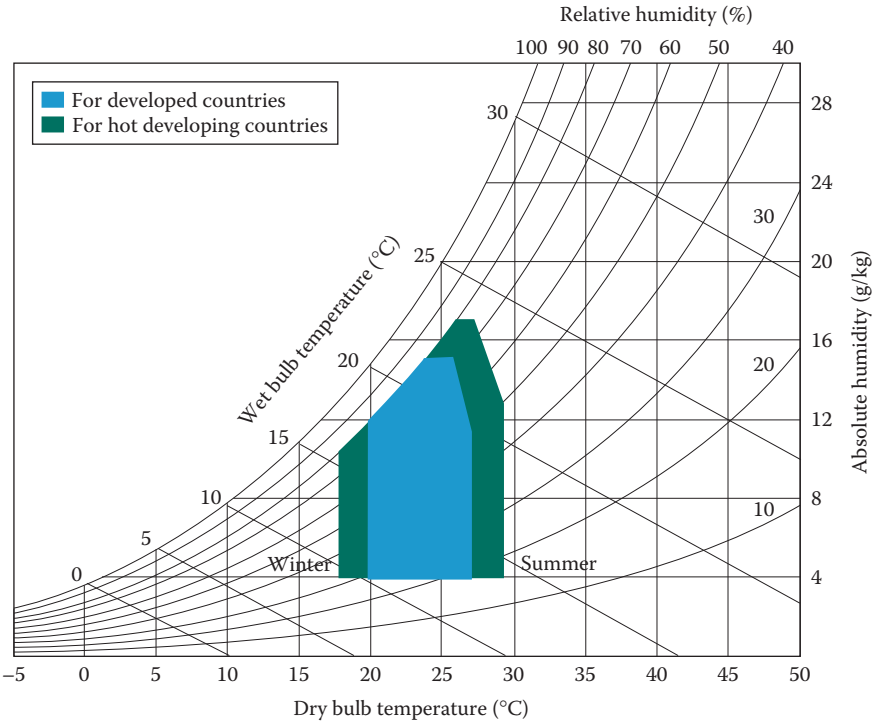


FIGURE 6.10 Givoni's comfort zones for groups in developed and hot developing countries.

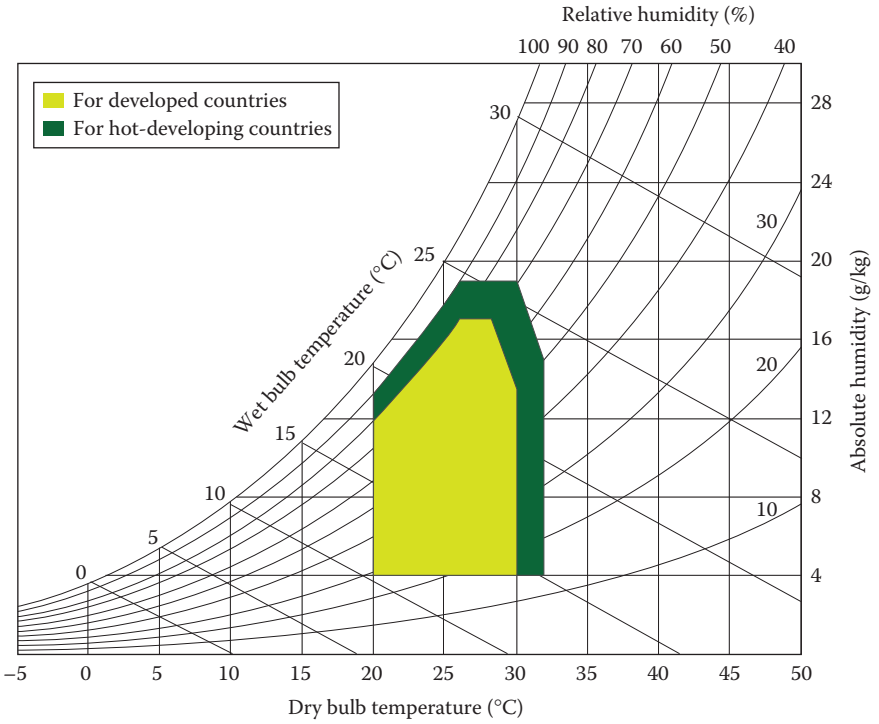


FIGURE 6.11 Givoni's for comfort ventilation in developed and hot developing countries.

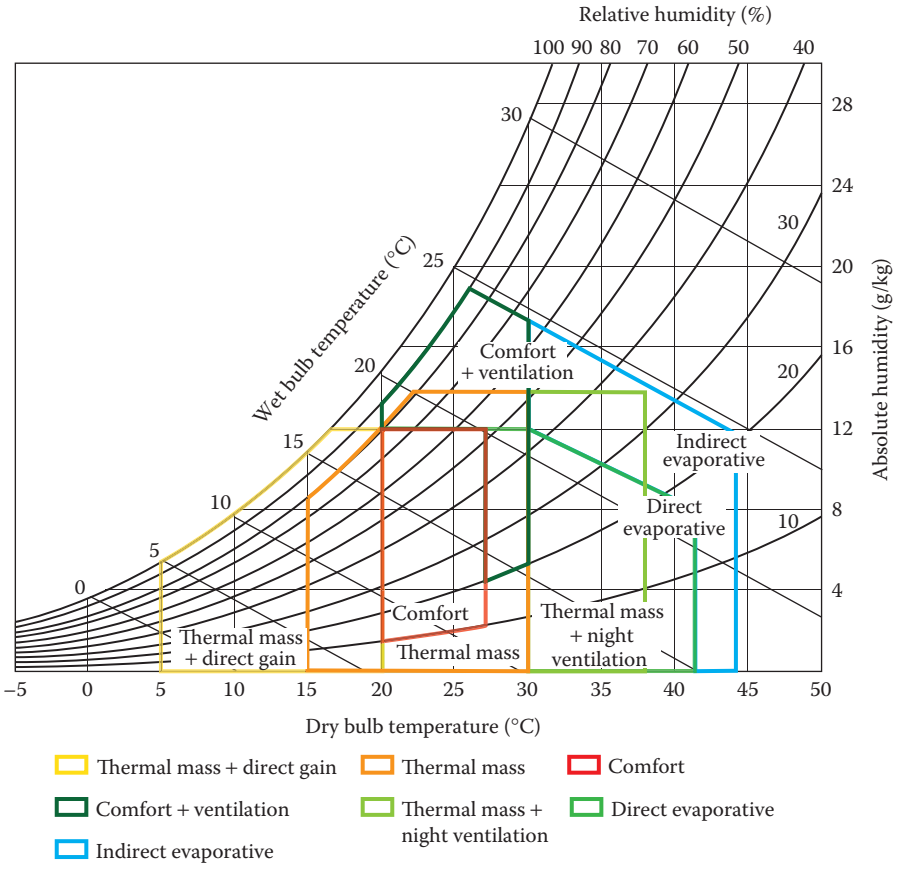


FIGURE 6.12 Proposed building bioclimatic chart with strategies.

(cooler or warmer), bringing them closer to thermal comfort. As building technology evolves and improves, the boundaries of all the strategy zones will extend farther and farther away from the comfort zone, and it will be possible to design climate-responsive low-energy buildings under more difficult conditions.

Conditions toward the left of the comfort zone are cooler than comfort, indicating that heating must be implemented to achieve comfort. Conditions toward the right of the comfort zone will require implementation of a cooling strategy. As the points are farther away from the comfort zone in either direction, more heating and cooling are required. After a certain point, it is not possible to heat or cool the building solely with passive means and mechanical systems will be implemented.

6.5.3 Digital Climate Analysis Tools

As described in Section 6.2, digital climate analysis tools can process yearly data that are available in several weather file formats such as EPW and weather (WEA) to present data graphically so that it is easier to process and understand, even though it is statistical, not real. The ability to process yearly data files is the main advantage of these digital tools; however, it is also their main limitation. If a yearly climate data file is not available, then it is not possible to do any analysis at all unless data are interpolated from nearby stations or data are used from a similar location and organized in

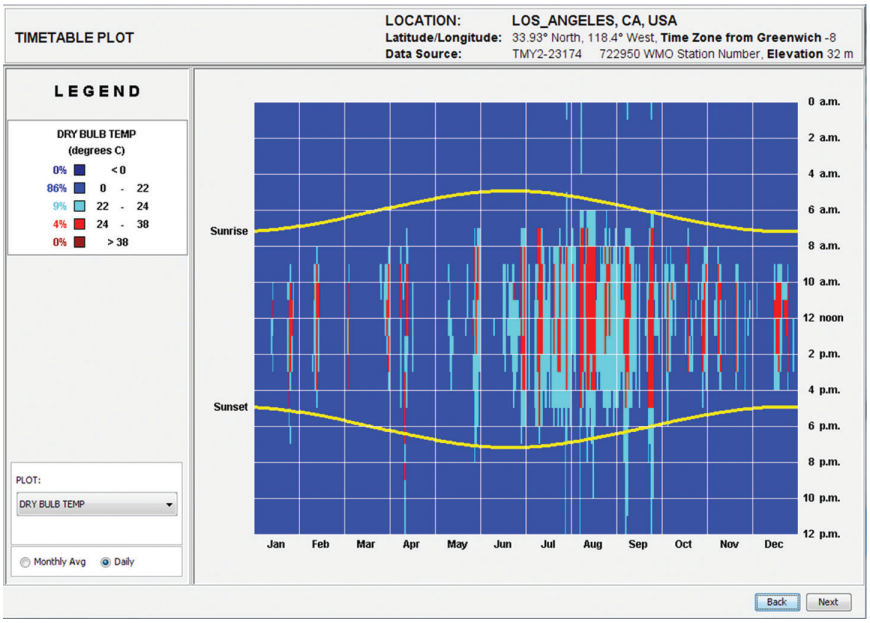


FIGURE 6.13 Timetable of bioclimatic needs from Climate Consultant.

a readable form. Weather analytics and Meteonorm can generate weather files for different locations by interpolating existing weather files. Rodriguez (2008), a professor from Universidad del Zulia in Venezuela, developed a simple climate analysis tool called Clima that cannot process annual climate files, but it has the advantage of processing manually introduced data (minimum and maximum average monthly values) providing more opportunities to process information from any location in the world, which it plots in a psychrometric chart using Givoni's comfort zones for developed and less developed countries.

All of these newer digital tools incorporate the use of concepts such as the BBCC and the timetable of bioclimatic needs. The latest version of Climate Consultant (Milne, 2011) also provides multiple comfort models such as the California Energy Code comfort model for 2008, the *ASHRAE Handbook of Fundamentals* comfort model (2005), ASHRAE Standard 55-2004 using the predicted mean vote (PMV), and the adaptive comfort standard in ASHRAE Standard 55-2004. In addition, it provides many useful options to visualize and better understand data. Figure 6.13 shows a digital version of Olgyay's timetable of bioclimatic needs, plotted from Climate Consultant. Hourly temperatures are plotted in the table and are color coded according to their temperature range, which gives an idea visually of the yearly temperature range and the temperature location in one single image. Figure 6.14 shows a wind wheel developed by Milne and Al-Shaali for Climate Consultant, which in addition to wind direction and frequency includes air temperature and relative humidity information and can be studied in yearly or monthly increments.

6.5.4 The Comfort Triangles Chart

Evans (1998) developed another climate analysis tool called the comfort triangles chart. This climate analysis tool was originally proposed by Evans and de Schiller (1998) and then further developed by Evans (2003, 2007). In his chart, Evans also uses two variables to characterize conditions in a specific moment; however, instead of using dry-bulb temperature and humidity, he proposes using

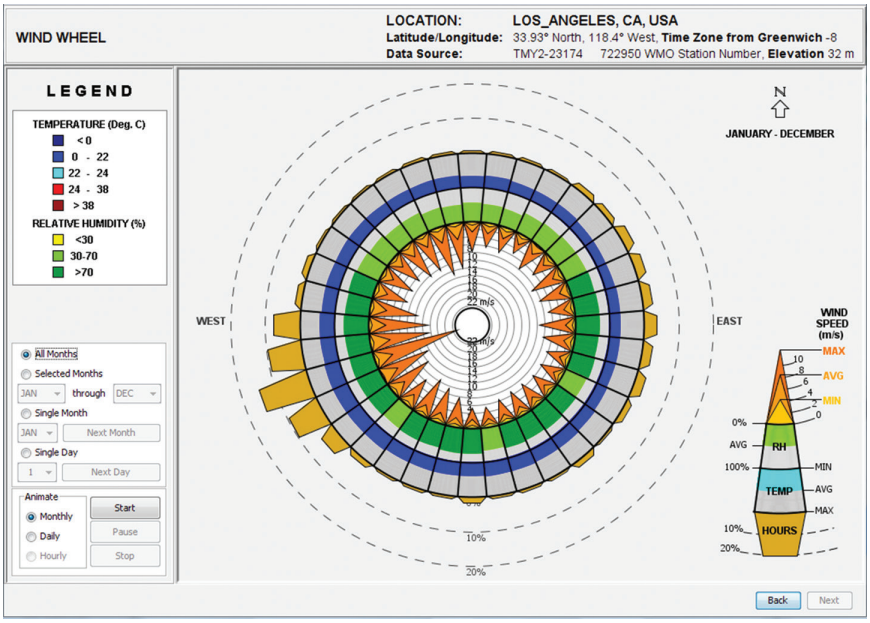


FIGURE 6.14 Wind wheel from Climate Consultant.

the daily temperature swing and average temperature because these characterize the temperature variations during a daily cycle. The average temperature is plotted on the *x*-axis, and the swing is plotted on the *y*-axis. The chart indicates the four different zones for sedentary activities, sleeping, circulation, and extended circulation in addition to the bioclimatic strategies that can be applied to improve comfort when the conditions are outside the comfort zones: sensible air movement; thermal inertia, which combines time lag and thermal dampening; solar radiation; and thermal insulation and selective ventilation (Figure 6.15). As with other climate analysis tools, the analysis of the outdoor data leads to design strategies that can be implemented to achieve thermal comfort. Evans (2007) validated his system in several climates with positive results.

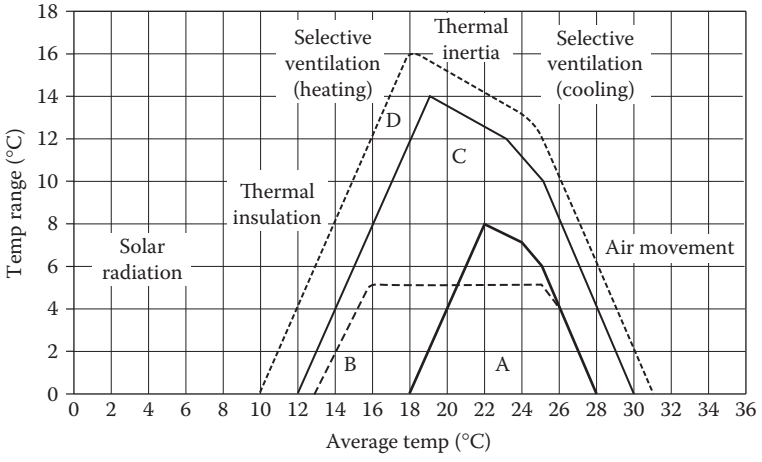


FIGURE 6.15 Comfort triangle charts. (From Evans, M. The Comfort Triangles: A New Tool for Bioclimatic Design. PhD thesis. Delf Technical University, 2007. With permission.)

6.6 VERNACULAR ARCHITECTURE

Even though climatic determinism fails to account for the range and diversity of house forms, climate is, nevertheless, an important aspect of the form-generating forces, and has major effects on the forms man may wish to create for himself. This is to be expected under conditions of weak technology and limited environmental control systems, where man cannot dominate nature but must adapt to it. … The principal aspect to be examined is the amazing skill shown by primitive and peasant builders in dealing with climatic problems, and their ability to use minimum resources for maximum comfort" (Rapoport, 1969, p. 40).

Primitive and preindustrial builders learned to solve their problems by collaborating with nature. The buildings were designed to protect their way of life. If the building failed, then the owner would be exposed to the potentially harsh forces of nature. These buildings show respect for the environment, and it is possible to learn from them. It could even be argued that the bioclimatic concept, and the now more global and comprehensive notion of sustainable architecture, extends with scientific methods the ecologically responsible concepts transmitted through many generations, based on an intuitive knowledge of the environment and the climate.

6.6.1 Vernacular Architecture in Warm, Humid Climates

In a warm and humid climate, overheating is not as significant as in hot and dry areas, but conditions are aggravated by high humidity, which limits the evaporative cooling effect. These climates have at least 1 month of the year with a temperature higher than 20°C and a mean relative humidity around 80%. The monthly rainfall is often above 200 mm, mostly in the form of short-duration, high-intensity showers.

A vernacular building in a hot and humid climate is usually lightweight, very open to the winds to promote evaporative cooling, and with a large roof that extends over the walls to block solar radiation (Figure 6.16). There are many variations of this model, but vernacular buildings like this can be found in hot, humid climates all over the world, from the South Pacific to the Caribbean. Because it was so important to provide natural ventilation to these buildings, they were usually spread apart so that they would not block breezes from each other.

The churuata is the typical dwelling of several ethnic groups in southern Venezuela, both in the Gran Sabana and the Amazon region. The churuatas of the Piaroa, Ye'kuana, Hoti, Panare, and Pemon are similar but not identical; each ethnic group has its own characteristic construction,

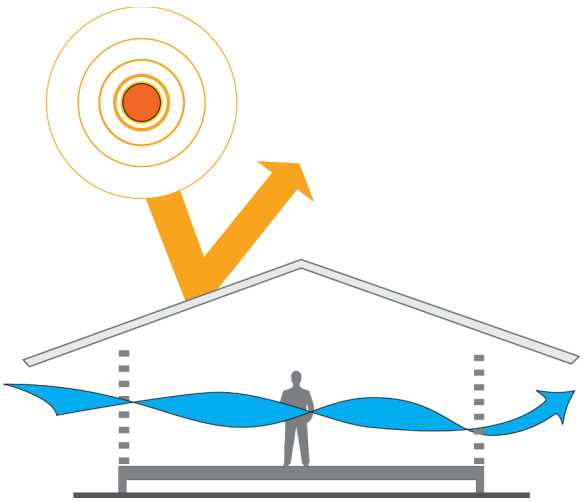


FIGURE 6.16 Hot and humid climate archetype.

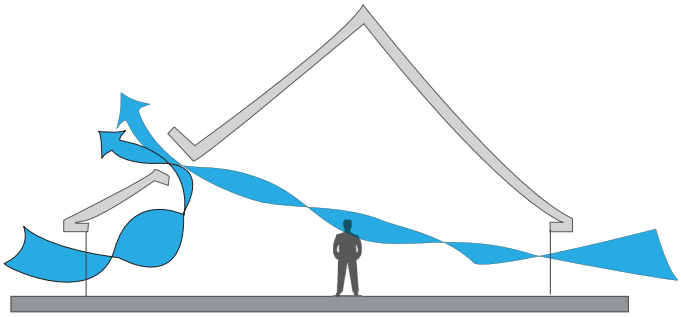


FIGURE 6.17 Yekuana churuata in Venezuela and Brazil. (Courtesy of P. La Roche.)

all with great formal beauty (Gasparini, 1993). The Piaroa have a tendency to elevate the height of the conical roof, and some have oblong plans with rounded ends. Usually the bottom of the churuata consists of a peripheral mud wall and a thatched roof that accounts for most of the building envelope (Figure 6.17). The bottom wall has enough shaded thermal mass to modulate temperature, while the upper roof provides shade and stores humidity from the air, lowering the air temperature by evaporation. Most of the churuatas have an opening in the roof for sunlight and evacuation of hot air (Figure 6.17). Interior compartments give some privacy to its dwellers.

Many Native American communities developed their settlements by the riverbanks or lakes, which were used for communication. These dwellings were raised above the water, on pilings, and construction elements were simplified to the extent that many of their houses simply became a roof on top of wooden poles. Other environmental factors such as the height of the maximum tides and floods were also taken into consideration in their design. An example is the dwellings of the Paraujanos in the Maracaibo Lake Basin in western Venezuela. These buildings perform as an inhabited filter in which the different components of the envelope—floors, walls, and ceilings—are permeable; sunlight, wind, dust, and water are regulated by these three components (Machado, La Roche, Mustieles, and De Oteiza, 2000). The floor, built with mangrove cane poles, permits cool air from the water below to filter inside the building. The walls, also made of cane poles or thatch, are permeable to the light and wind, filtering in the light (Figures 6.18 and 6.19). The ceiling, thick and built with enea, a type of thatch, allows the house to breathe and evacuates the heat but blocks the rain. Because it is opaque, enea also blocks most of the solar radiation to the interior of the building, effectively shading the interior. This type of house is still built today, even in urban settings, but

FIGURE 6.18 Paraujano house in Venezuela. (Courtesy of P. La Roche.)

FIGURE 6.19 Paraujano house in Venezuela. (Courtesy of C Quiros.)

unfortunately many of the original materials have been substituted with contemporary materials such as industrialized tin and zinc, with a longer life span but much reduced performance.

Some contemporary proposals in the Sinamaica Lagoon, such as the community center and church designed by the author and built by the Corporation for the Development of the State of Zulia, considered local architecture and materials (Figure 6.20). In the meeting room, for example, the air filters through the mangrove poles, providing natural ventilation with air that is cooled as it passes above the water. These poles are further separated above the door lintel to increase airflow inside but to maintain certain privacy at the lower level.

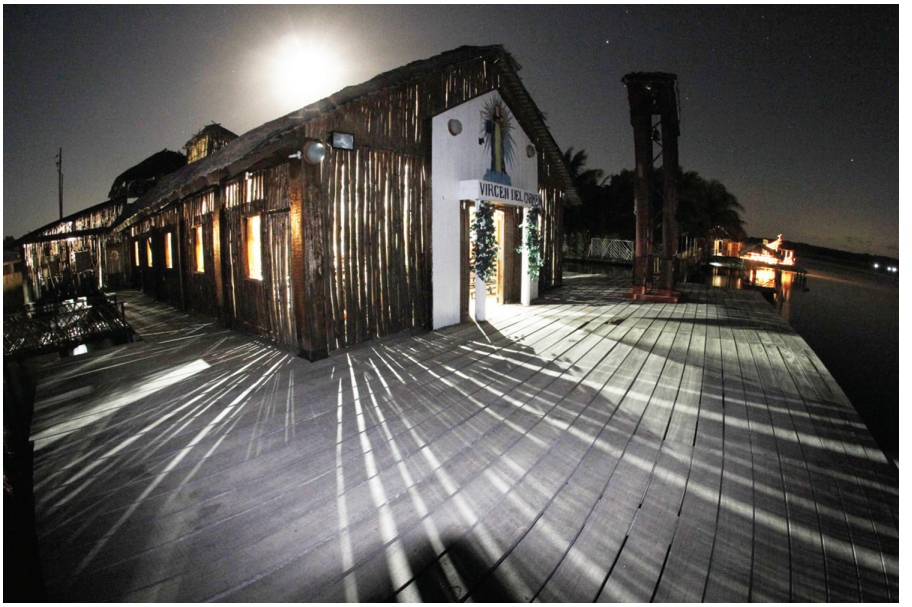


FIGURE 6.20 Paraujano Community Center in Venezuela. (Courtesy of C Marval.)

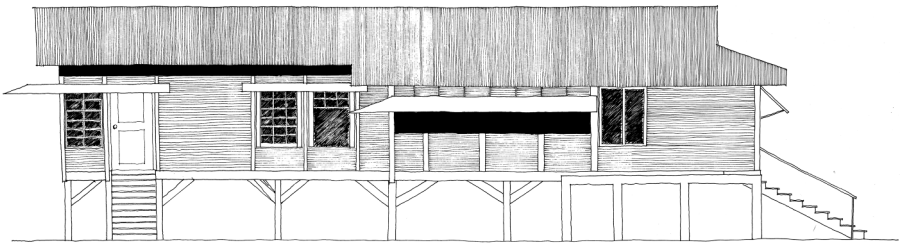


FIGURE 6.21 Standard Oil Company house in Maracaibo, Venezuela. (Courtesy of Maria Gabriela Romero.)

An interesting example of nonvernacular architecture adapted to a warm and humid climate is the architecture for oil and fruit companies of the early to mid-twentieth century. This architecture was the result of the research and experience of Dutch, British, and American transnational corporations sometimes associated with researchers and universities, and many variations of these buildings can still be seen all over the world. These houses were usually detached rectangular buildings, completely surrounded by gardens, and most often with light-colored facades, with their windows and doors protected by a large roof or "big hat." The roof generally had four slopes, with metal sheets and a ventilated attic, above a wooden or metal structure (Figures 6.21 and 6.22). The exterior walls were usually made of wood or metal, sometimes with an air space, and provided relatively good insulation for their time (La Roche, 1992). These homes, which were designed to be climate responsive, have continued to evolve and generate a local vernacular language in many regions of the world. Figure 6.23 shows one of these in Panama, while Figure 6.24 shows another one in Kuai, Hawaii.

FIGURE 6.22 Standard Oil Company house in Maracaibo, Venezuela. (Courtesy of Pedro Romero.)

FIGURE 6.23 Hot, humid contemporary vernacular in Panama. (Courtesy of P. La Roche.)

FIGURE 6.24 Hot, humid contemporary vernacular in Kuai. (Courtesy of P. La Roche.)

6.6.2 Vernacular Architecture in Warm and Dry Climates

The main problem in a hot, dry climate is overheating (i.e., inadequate heat dissipation from the body), but because the air is dry, evaporative cooling can take place. High temperatures and radiation characterize such climates, and the mean temperature of the warmest months is above 27°C with a low relative humidity. The yearly maximum temperature is around 45°C, and the minimum can be as low as –10°C, which is a large temperature swing.

A building in a warm and dry climate is usually a compact heavy mass structure that modulates outdoor temperatures, with small windows to reduce solar gains to the interior of the space but that allow some ventilation for night cooling (Figure 6.24). Because of the need to reduce solar gains, the building layout is also compact, reducing the amount of exterior surface exposed to the sun, receiving direct solar radiation. Controlling natural ventilation allows the occupant to capture nighttime temperatures in the interior thermal mass, cooling the interior of the space, which then acts as a heat sink during the daytime absorbing heat and keeping it cool through the day. The effect of thermal mass by itself reduces the daily indoor swing (Figure 6.25) so that indoor temperatures are not as extreme, and the resulting indoor temperature fluctuates somewhere close to the average of the outdoor temperature. When the user has the ability to control ventilation and night flushing is provided, the indoor temperature swing is still lower than the exterior swing, but the resulting indoor temperature is shifted lower and closer to the outdoor minimum temperature (Figure 6.26). The reduction of the indoor temperature is a function of the amount of thermal mass, the air change rate during the night, and solar control during the day, usually as insulation, shading, and reduced infiltration (Figure 6.27).

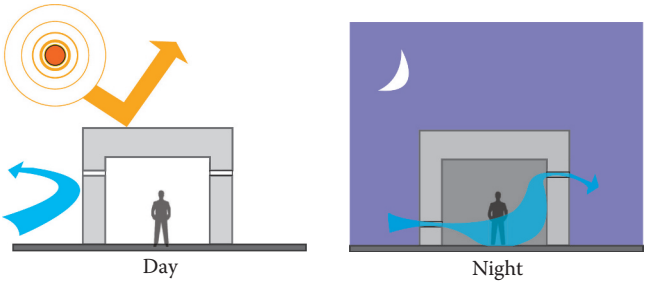


FIGURE 6.25 Hot and dry climate archetype.

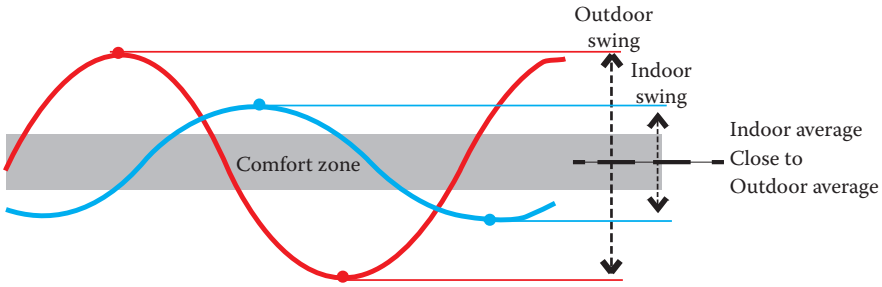


FIGURE 6.26 Effect of thermal mass on indoor daily temperature swing.

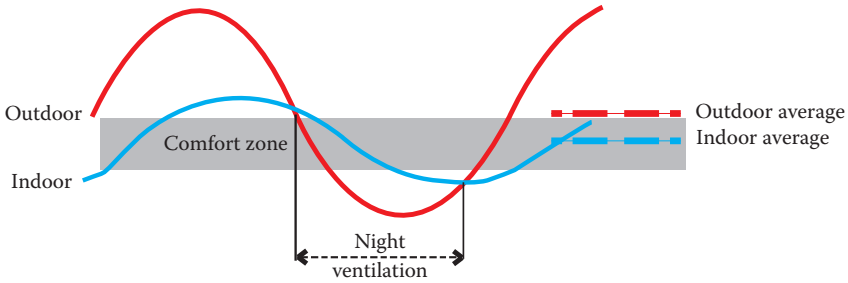


FIGURE 6.27 Effect of thermal mass and night ventilation on indoor daily temperature swing.

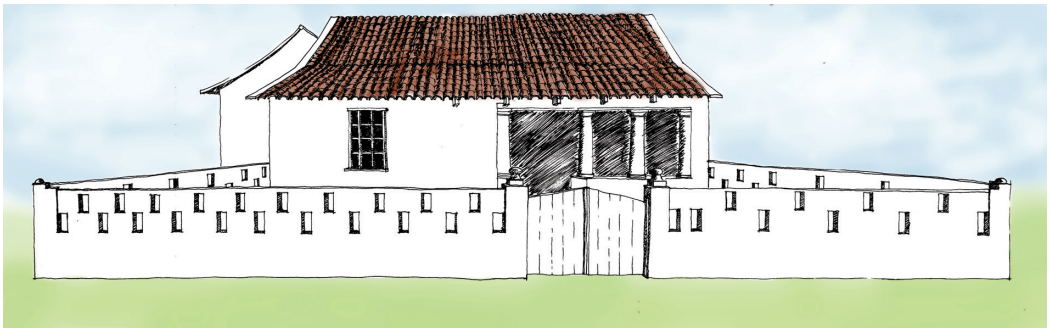


FIGURE 6.28 Hato (small farm) in Falcon, Venezuela.

The *hatos*, or small farms, of the Paraguana Peninsula in Venezuela (Figure 6.28) are generally compact to reduce surface area exposed to solar radiation and to increase the amount of mass per dwelling and thus thermal inertia, which flattens temperature swing. The exterior color of these hatos is usually white, which reflects a large amount of incident solar radiation. Openings toward the outside are few and small, and there might be an outdoor transition space. The control of openings is very important: They must be closed during the day to avoid heat gains by radiation and convection and open during the night to permit the entry of cooler air that will lower the temperature of the mass inside the hato. Most of these houses were built using either adobe bricks or bahareque walls as the primary material for the walls, both of which have high thermal inertia. This mass also generates thermal lag with indoor temperatures that are sometimes uncomfortable during the night. Hatos are sometimes open to planted courtyards, and the kitchen is usually toward the southwest, permitting the northeastern trade winds to carry heat, smoke, and smells away from the house.

In Andalucia, Spain, compact buildings are organized around courtyards that are not only beautiful but also help to regulate climate by controlling radiant, convective, and conductive gains and losses (Reynolds, 1992). Shading to block solar heat gains is usually accomplished with toldos, moveable fabrics with varying degrees of translucency that block most of the direct solar radiation but permit diffuse light to penetrate (Figure 6.29), and some direct light that generates lively shadow patterns. These toldos can be opened at night to promote radiant cooling to the night sky from the courtyard, especially from the sky-facing floor. Some patios also use trellises and vines for shading but these do not have the operability of the toldo. The mass in the courtyards is a thermal regulator that reduces daily temperature swings. This mass, especially the sky-facing floor, is cooled at night by radiation to the night sky, and also by evaporation and ventilation. During the daytime this thermal mass then acts as a heat sink delaying, with the aid of the toldos, the arrival of the afternoon heat. By their radiant effect these cool surfaces also contribute to the comfort sensation. Plants also have an important role in these courtyards; they are not only a delight to the senses but also demand caretaking and watering, which then provide through evaporation a major source of courtyard cooling in hot weather (Figure 6.30). Fountains and other bodies of water in the courtyard also provide additional opportunities for evaporative cooling.

Orientation and additional geometrical properties also affect thermal performance of these courtyards. The aspect ratio, which is the area of the courtyard floor to the average height of the surrounding walls, determines the degree of openness to the sky. The greater the aspect ratio, the more exposed this courtyard is to the sky allowing more heating during the day, and more floor surface facing the sky that can be cooled at night, and also more possibility for wind entry. The solar shadow index is the south wall height over the north–south floor and determines the amount of winter sun exposure. A higher index means that the courtyard well is deeper and less winter sun will reach its floor. There are many

FIGURE 6.29 Courtyard in Cordoba with Fountain and Toldo. (Reprinted with permission from Reynolds, John S., *Courtyards: Aesthetic, Social, and Thermal Delight*, John Wiley & Sons, Hoboken, NJ, 2002.)

different combinations of orientation and aspect ratios and the solar shadow index that affect how the courtyard receives solar radiation.

Different sources define temperate climates in different ways. The definition stating that a temperate climate has some heating and cooling requirements but that neither is very severe is the one that is used. However, there are many variations of this, and some temperate climates may have both a winter and a summer with rather severe variations in each. This is especially true in mid latitudes and inland of large continents such as North America and Asia (Moffat and Schiler, 1981). The mildest form of a temperate climate is modulated by masses of water and is the climate of the Mediterranean, much of the California coast, and many Latin American cities that are further away from the equator or at a higher altitude.

In inland temperate climates, a building has to respond to relatively warm summers and cold winters. Thus, the building must keep the heat inside in the winter, protecting from the cold winds while providing daylight. During the summer, the building must keep the heat outside, while also providing shade and ventilation. This means that an archetype in this climate should be compact, well insulated, and tight. In the coastal or milder areas the outdoor conditions are much milder with less temperature differences between the summer and the winter. Therefore, there is more flexibility

FIGURE 6.30 Potted plants on patio in Cordoba. (Courtesy of Lucia La Roche.)

in the design of the building as long as it provides shade and opens to the cool summer breezes in the summer, and protects from the cold wind, while providing some passive solar heating in the winter (Figure 6.30).

6.6.3 Vernacular Architecture in Temperate Climates

A temperate climate usually has some heating and cooling requirements, but neither is very severe. This is the climate of the Mediterranean, much of the California coast, and many Latin American cities that are further away from the equator or at a higher altitude. There is no real archetype for a temperate climate because it is so forgiving that almost anything can be done as long as the building opens to the cool summer breezes and closes to the colder winter air while providing some passive solar heating (Figure 6.31). The overhangs and layout of the building should be adapted to latitude and provide solar radiation and shade as needed.

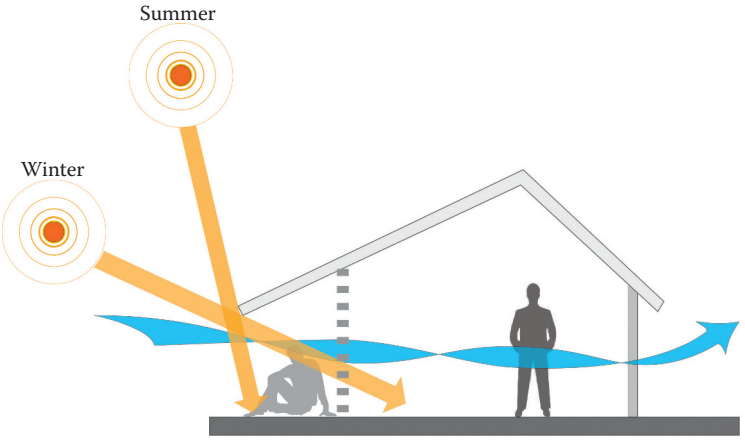


FIGURE 6.31 Temperate climate archetype.

FIGURE 6.32 Veranda in Quinta Anauco, Venezuela. (Courtesy of Carlos Quiros.)

The Spaniards arrived in America in the late fifteenth century with a housing typology that incorporated principles of traditional southern Spanish dwellings. This model was implemented with variations adapted to different climates. Variations included building massing and orientation, window size and position, layout of the building, verandas, courtyards, and interior layout of the spaces. Most Latin American colonial architecture in temperate climates includes extensive use of verandas and courtyards (Figure 6.32). Many of these buildings such as the *haciendas,* or large farms, had large windows to promote ventilation and shaded external corridors in contact with gardens. Convents and monasteries were organized around courtyards for daylight, natural ventilation, and even collection of water (Figure 6.33).

Colonial residential buildings also had one or more courtyards for natural ventilation and illumination. At the front of the house toward the street, there usually was a bedroom and a living room, while the entrance was through a hallway called the *zaguan*. The dining room was toward the middle; the kitchen, the laundry, and a multipurpose room sat toward the back and opened to an L-shaped courtyard.

There are many qualities worth preserving in Spanish colonial architecture; however, one that is often overlooked is the colonial window, which is a very good example of how windows can combine different components to provide different functions (Figure 6.34). Venetian blinds or wood louvers reduce sunlight as well as the intensity of light. They do not retain heat or let it go inside, yet they let air and breeze slip through. They also preserve privacy: You can look out without being seen (Figure 6.35). Waterproof wooden shutters protect from unwanted rain, wind, or dust; in many cases they have a small upper glass window that provides the inside with proper lighting even in the most adverse weather. Wooden bars separated from each other by no more than 15 cm provide security.

FIGURE 6.33 Courtyard in Mexico city used for daylight and natural ventilation. (Courtesy of P. La Roche.)

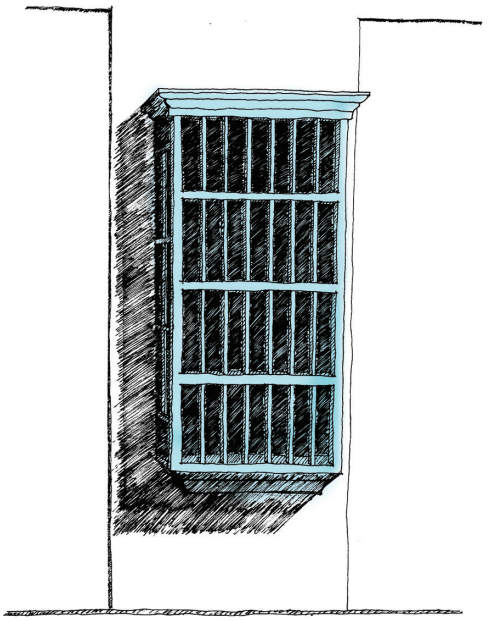


FIGURE 6.34 Typical Spanish colonial window in Maracaibo, Venezuela. (Courtesy of P. La Roche.)

FIGURE 6.35 Colonial facade with several windows in Maracaibo, Venezuela. (Courtesy of R. Cuberos.)

Because the windows protrude outward, communication with bystanders or neighbors is promoted, thanks to an indoor bench (Machado et al. 2000).

6.6.4 Mid-Century Architecture in Temperate Climates

The connection of mid-century Los Angeles architecture with nature has been frequently discussed and mentioned. The importance of climate in the design of these houses has been stated by some authors such as Ester McCoy "… it was the California sun rather than the hearth that was at the base of the Case Study houses" (McCoy, 1989). Several papers by the author have studied the relationship of these houses with the environment (La Roche, 2001) (La Roche, 2002) (La Roche, Almodovar, 2009) (La Roche, Naversen, Jamison, 2013) (Alonso, La Roche, Oteiza, 2016). We interviewed owners and some of the architects, performed digital daylight analyses and measured daylight levels on-site, studied utility bills over many years, installed data loggers to record temperature and relative humidity, and performed carbon footprint calculations. Some of the results from that research are presented here.

At a latitude of 34 degrees north, Los Angeles has a mild Mediterranean climate with summer temperatures between 29°C and 18°C and winter values between 19°C and 9°C. According to ASHRAE Los Angeles has 1495 average annual HDDs, base 65, and 4306 annual average cooling degree hours, base 74; and from 8 a.m. to 4 p.m. there are 1849 hours a year with temperatures between 55°F and 69°F, with only 145 hours below 55°F for this same hour period. Cool ocean breezes are common during the whole year, and only for several days a year conditions are reversed when warm air blows from the desert. Most of the rainfall is during the winter months of January and February.

However, even though the buildings are located relatively close to each other, there are many differences due to micro-climates created by the topography and the effect of the Pacific Ocean. The Schrage House designed by and located experiences a 26°C average annual temperature differential, while the Kappe house in Pacific Palisades only experiences an 11°C temperature differential and is cooler in the summer and warmer in the winter. Both houses are located in a hilly terrain, but the Kappe house is located a mile from the coast while the Schrage House designed by Pierce Koenig is 15 miles from the coast and less subject to the ocean's effect.

Schindler wrote of his ideas on comfort through natural means in 1926,

> Useful as our heating systems may be … their basic principle is faulty. … Anyone who has experienced the stimulating effects of a cool pure breeze on a sunny mountaintop … will realize that the old campfire uses a more wholesome method of heating than all of our complicated modern plants. The house of the future will provide cool, clean, constantly changing air, but will keep us warm by means of direct heat rays emanating uniformly from the walls and the ceiling. (Steele, James, 2005)

The occupants of the Kallis house designed by are aware of the lack of insulation, mentioning in their interview, "There is no insulation here. … That certainly makes you aware of living in the climate that you're in" (Sharlin, Jackie. Video Interview by Sakamoto, T. November 2012).

6.6.4.1 The VDL Garden House by R Neutra

Neutra built his VDL house to promote "biorealism"—a concept he defined as people being in harmony with nature and themselves. The VDL house was Neutra's living laboratory to provide lessons about human scale and interaction with the natural environment that could be applied to work for larger public projects. He strove to "achieve a privacy and spacious living despite the constraints and density of the urban neighbourhood," stating this was possible through discovery of the "profound assets rooted in this site and buried in it like a treasurable wonder." He considered the landscape and architecture equally in design, paying careful consideration to views, sources of wind, and the changing positions of the sun (Tadashi, 1998).

The Garden House was a guest house added to the primary residence in 1939, seven years after the earlier construction. Neutra closed off the back garden into a courtyard with the building of the new T-shape structure, adding an asymmetrical volume to the pure geometry of his international style home (Lamprecht B, 2004) (Figures 6.36 through 6.39).

Prevailing breezes arrive off of the Silver Lake Reservoir across the street to the west of the house. The Air is able to pass through the house into the central courtyard between the main house and the Garden House. Shaded by the higher structure, and cooled by ventilation, foliage, and evaporation from the reflecting pond, the Garden House enjoys a cool micro-climate facing the courtyard. Over time, the front windows of the VDL house have been closed off due to street noise and pollution. These changes have reduced some of the potential benefits of natural ventilation through the house when cooling is needed, although many of the large windows are still operated by its occupants.

FIGURE 6.36 VDL Garden House. (Courtesy of Kenneth Naversen.)

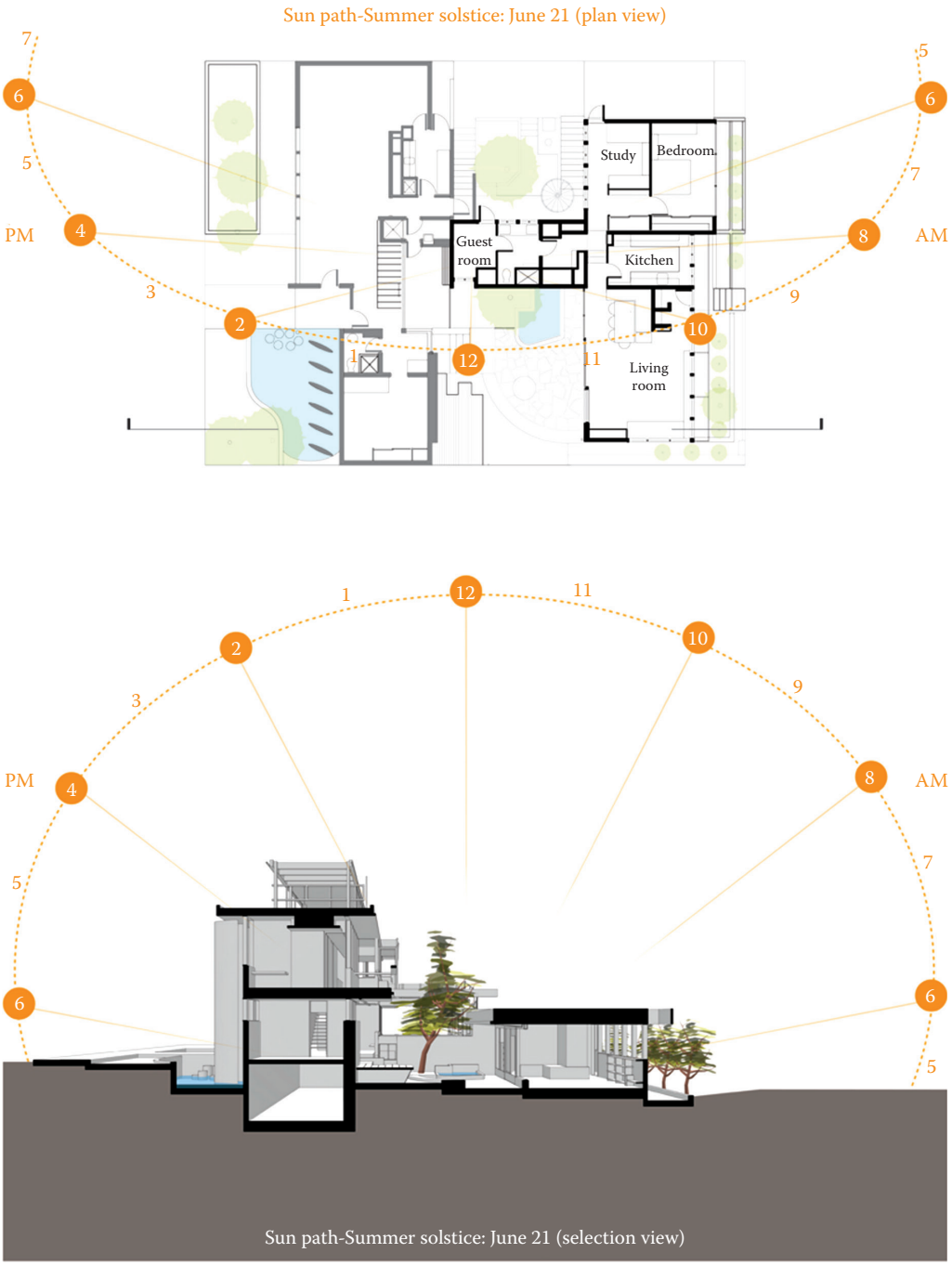


FIGURE 6.37 VDL Garden House and summer sun path diagram.

6.6.4.2 Case Study House 22

Another interesting example of climate-responsive buildings is the Case Study Houses in Los Angeles. The Case Study House program was sponsored by John Entenza's *Art and Architecture* magazine between 1945 and 1966. During this period, 36 experimental prototypes were designed and many of them built. Even if the words *sustainability* or *green architecture* did not exist at that time, these buildings already

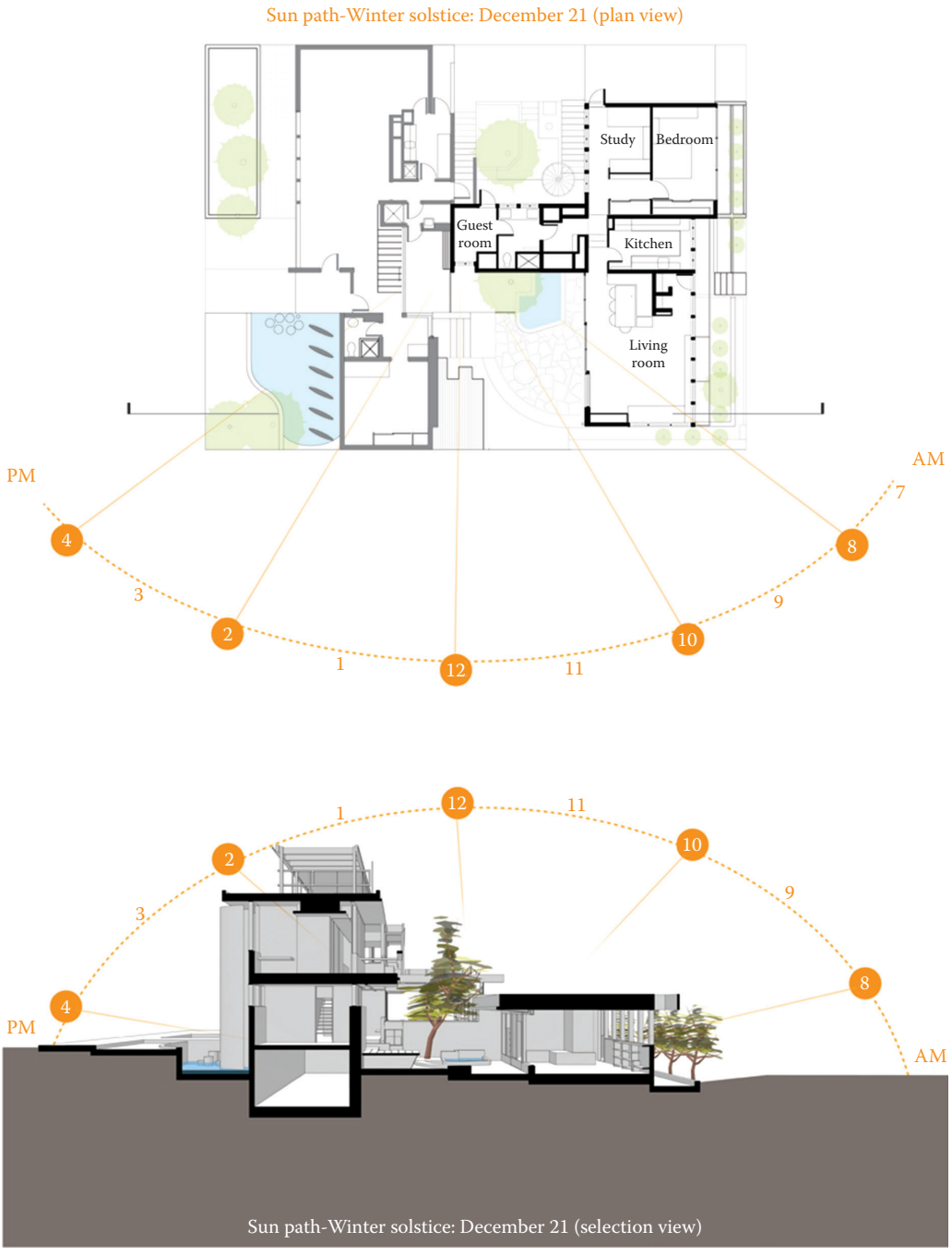


FIGURE 6.38 VDL Garden House and winter sun path diagram.

exhibited many of the attributes of contemporary green buildings. The large operable windows and doors not only were open to the views but also permitted the flow of air in the summer while permitting solar radiation in winter (Figure 6.40). The climate-responsive strategy of allowing free flow of space inside the modernist architecture of the Case Study Houses was an architectural design strategy to make small buildings feel larger (La Roche, 2003; La Roche and Almodóvar, 2009). The ability to ventilate,

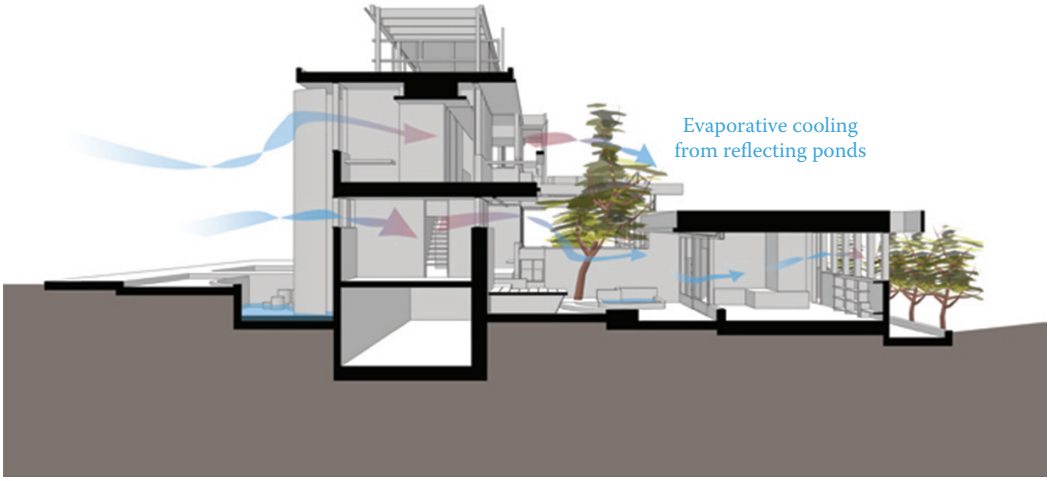


FIGURE 6.39 Natural ventilation, cooling breezes from the Silver Lake Reservoir through the VDL house.

FIGURE 6.40 Large operable windows such as those in Case Study House 22 were common.

combined with summer shading and good site design, made most of these Case Study Houses effective in the summer, but the large amount of single-pane windows did not permit them to perform well in the winter and, in some cases, promoted overheating in the summer.

Case Study House 22 was designed by Pierre Koenig and completed in 1960 for Carlotta and Buck Stahl. It is located in the Hollywood hills above Sunset Boulevard in West Hollywood, Los Angeles. With its pool and panoramic view across the city, it is probably the archetypal Southern Californian "good-life" house and is now a protected Los Angeles County architectural landmark.

The plan consists of two wings forming an "L" at 90 degrees to each other and about the same size. The east-west wing has a master bedroom and bath and a children's bedroom, which can be subdivided into two smaller rooms with WC and shower. There is a continuous line of storage cabinets mounted high on the solid wall lining the street to the north. The north-south wing comprises the cooking, eating and living areas. The kitchen is made of prefabricated cabinets, two stainless steel ovens and a stainless steel sink, with no full walls. The fireplace is also made of steel frame and open at its lower level to all four sides.

A detached layout has the maximum amount of elevations exposed to air currents and the "L" form of this house permits to further multiply the number of elevations open to the wind, with three elevations potentially open to the wind, which is the case of the living-kitchen wing

FIGURE 6.41 View of Case Study House 22. (Courtesy of Pablo La Roche.)

(Figure 6.41). The north-south wing also gives some shading to the east-west wing in the mornings, as if it was a large fin.

Because of the large amount of glazing, solar control, in this case provided by overhangs, insulation, and use of light colors, it is fundamental to avoid summer overheating. The sun penetrates the main living areas of the house early in the morning until around 11 a.m. and then in the late afternoon after 3 p.m. Curtains had to be placed in the east elevation, because the overhangs are not long enough to block solar radiation during most of the morning. The south overhang is quite effective as can be seen in Figure 6.42; most of the direct sunlight enters between November and February, when it helps to heat up the building. Mrs. Stahl also says that psychologically, they welcome this sun into their house in the winter. Insulation is provided by three ½″ thick (1½″ total) layers of rigid fiberglass on the roof and 4″ fiberglass in the walls. The north wall is now also covered with foliage, which acts as solar protection reducing gains to the house in the summer afternoons and mornings. Even though the building receives solar radiation during several hours of the day, when the windows are open, it is still comfortable because of the air movement and flushing of the warm air.

Three sides of the perimeter of the house are enclosed by 10- or 5-ft-wide sliding doors, which not only bring nature and views of the city of Los Angeles into the house but also, when open, generate air currents through the living spaces. As Mrs. Stahl says, "just opening the sliding door for a couple of feet generates a nice breeze." Opening the sliding doors by 2 ft is a 16 ft^2 opening. During the summer, the windows are generally opened in the morning, around 8:00 a.m., and closed around 8:00 p.m. This daytime ventilation prevents the building from overheating and cools quickly at night. The building does not have any air conditioning and is naturally ventilated in the summer; thus a huge amount of energy is saved during the summer compared to an ordinary, or even an energy-efficient, building.

Flexibility is a useful trait in sustainable buildings, and the application of a design and construction module generates adaptability. In Case Study House 22, Koenig determined the module as a

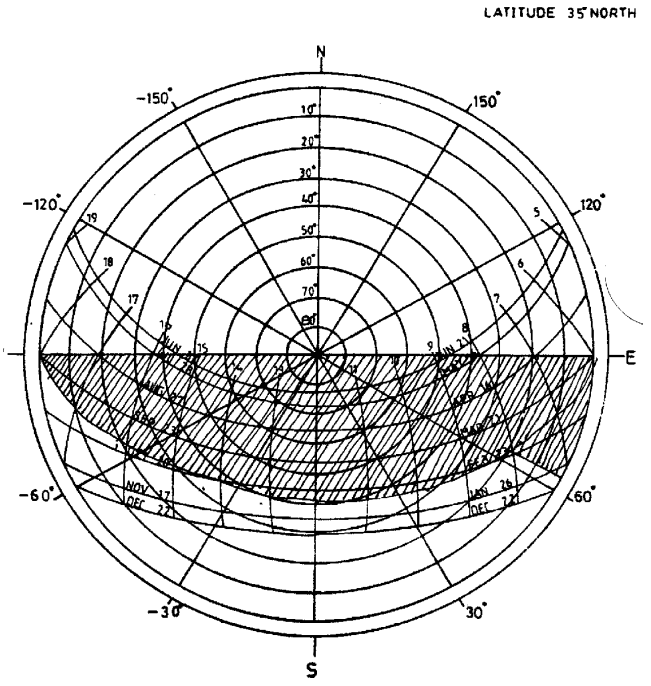


FIGURE 6.42 Case Study House 21 sun path diagram of South Façade.

function of the beam size to reduce waste and costs: only 2 steel sections were used: 12-in I-beams and 4-in columns, which create the 20 by 20 bays.

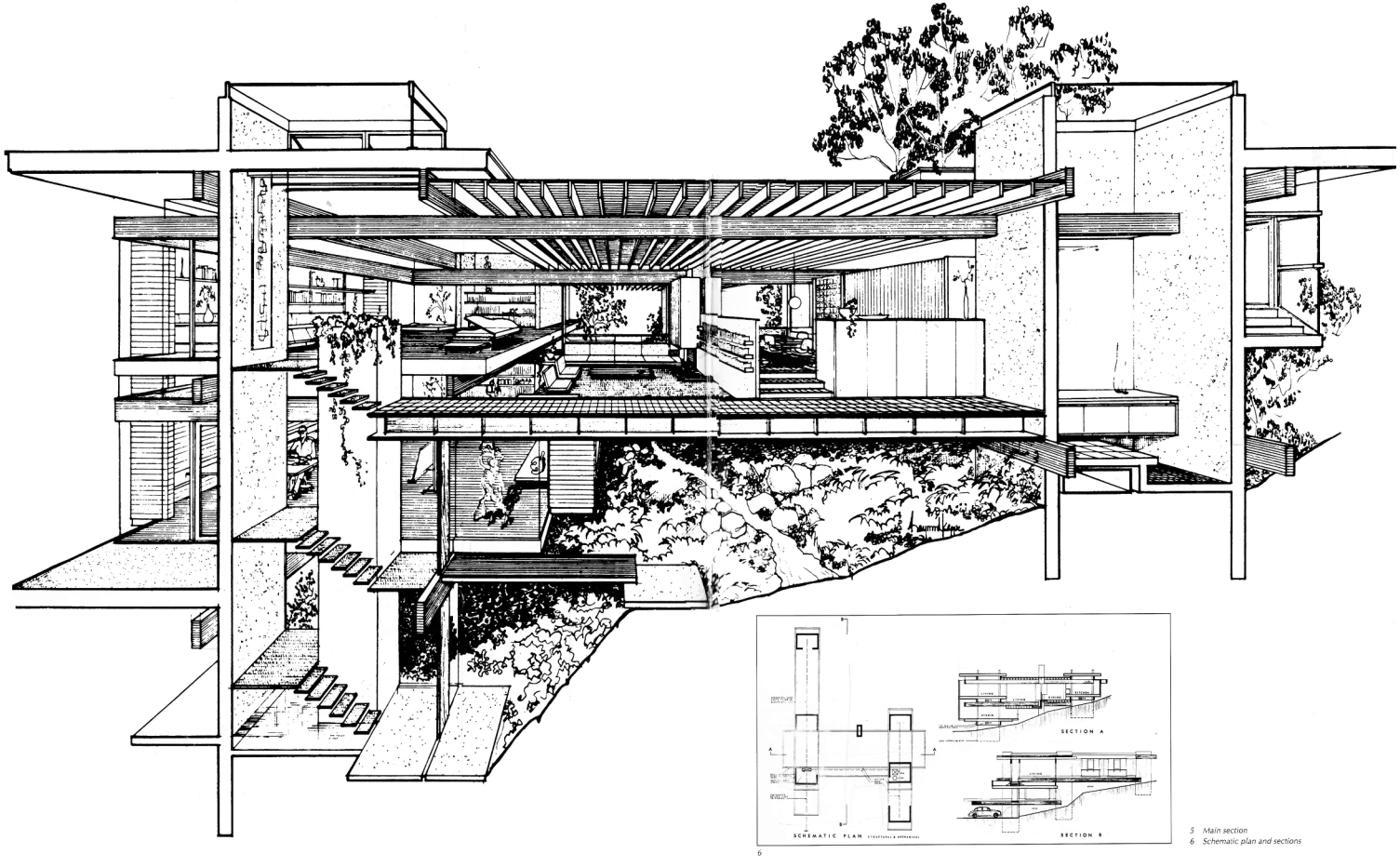
In 2001, the author placed data loggers in the center of the living room, 18 in below the ceiling and 24 in above floor level, in the center of the sleeping area at 6 ft above floor level, and outdoors in the shade. Indoor and outdoor temperature and humidity, from the data loggers, showed that indoor values have a smaller temperature range than outdoor values and are inside the comfort zone during most of the time and for a larger period of time than the outdoors. During warmer days a slight breeze provides comfort.

The temperature toward the lower level of the living room was generally lower than at the upper level, and stratification was greatly reduced, but not eliminated, when the windows were opened. Ventilation proves to be an effective strategy to flush out the warm air, maintaining indoor values at equal or even lower values than outdoors, probably due to the thermal capacity of the concrete floor.

6.6.4.3 Kappe House

The design of Ray Kappe's house is very driven by site conditions, the slope, and the springs, which determined the method of constructing the house by touching down as little as possible. As he explained, "I couldn't drive piling beyond where I'm sitting. I came to the conclusion to use these 6 tower units that would carry the house and I would bridge between them and cantilever as much as possible" (Figures 6.43 through 6.44). "The site comes 45 degrees to the house because I wanted the house to be parallel to the street, and that creates the step-up from the low point to the high point. Those were strong determinants in the process." (Kappe, Ray. Video Interview. November 2012.)

Architects like Kappe were aware of the importance of insulation and good glazing; however, they were also aware of the moderate climate. Most of these houses were not well insulated, and usually had extensive glass surfaces, so they are not particularly good examples of high-performance



5 Main section
6 Schematic plan and sections

FIGURE 6.43 Ray Kappe house on the site. (Courtesy of Ray Kappe.)

FIGURE 6.44 Ray Kappe house exterior. (© 2016 Timothy Sakamoto.)

buildings. However, because the climate is relatively mild and the buildings are shaded with numerous operable windows and sliding doors, they respond adequately to outdoor conditions and if the day is not too warm, usually better in the summer than in the winter. The act of connecting the outdoor with the indoor responded to a new attitude toward nature. This connection could not be achieved simply by increasing the size of the conventional window openings; a more drastic change was needed and thus floor to ceiling windows appeared.

As Ray Kappe said,

> Probably today you have to [use dual pane glass] to get by Title 24. That always bothered me in California. Our climate is not so severe that you have to do all that. We didn't think like that at all. Look back in the days when Schindler was doing his stuff and you were supposed to sleep outside and shoji panels let all the cold air through. It was a different time. We didn't even used to insulate hardly. I didn't insulate the walls at all because I had so much glass everywhere, what's the use in insulating a few pieces of wall. The roof was half inch Solitex, or one inch if you were extravagant. Today it's 4 inches. It's just a whole different way of thinking. (Kappe, Ray. Video Interview. November 2012.)

The Kappe's continuously use natural ventilation, especially in the summer (Figure 6.45). As Ray Kappe expressed in the interview,

> Normally the doors to the front deck are open. The other window down by my studio – that pretty much does this part of the house. On a hot warm day like today the house is cooler than the outdoors, so I open it up to let some warm air in. The concrete mass accepts the cold air so it takes a few hours for the house to warm up. You get the ocean air through the canyon – that does the job. Windows in bedrooms are open too. When it's cold we don't open it up as much. Shelley is particularly susceptible to breezes – we're really opposite – I like air and she doesn't – it affects her shoulders, so we don't open up as much when it's cool. (Kappe, Ray. Video Interview. November 2012.)

FIGURE 6.45 Ray Kappe house interior. (© 2016 Timothy Sakamoto.)

Ray Kappe starts using the radiant floor heating system around November and stops using it around March. According to Kappe, the trees and the sloped site shelter the house from cold winds in the winter. Deciduous trees in the front yard lose their leaves in the fall and allow solar heat gain through the SE glass doors off of the living room in the mornings. Direct solar gains through the southeast glass doors off of the living area warm the space by solar radiation.

In the winter Kappe usually wakes up around 7 a.m. and sets the thermostat to 70°F. In the morning and early afternoon the southeast-facing doors on the living room are cracked opened to allow for natural ventilation. Louvered windows in the bedrooms, upper living room, and studio are also cracked open for cross-ventilation. When Kappe is not working, he likes to sit in the living room and enjoy the view, watching the sun change and see the night coming in. Heating is necessary when the temperature gets down to the 40s and 50s at night, and the thermostat is set to 64°F, which usually happens only between October and March in the very early morning. Figure 6.46 shows recorded temperatures during a winter week in the house in 2013. The effect of the radiant heating system is evident. The temperature in the living room is also higher than in the study room, which is in the ground floor.*

6.6.4.4 The Occupant, the House, and the Climate

In these houses the occupant has always had an important role in achieving thermal comfort. They were engaged with the buildings and knew what to do to achieve and maintain thermal comfort. They knew when to open and close a window or when to open and close blinds. They even knew how to add elements to improve the performance. In some cases like the Schrage House, the Dodge's added large drapes to reduce heat losses in cool nights and to block solar gains when the overhang was not sufficient in the summer afternoon (Figure 6.47). These simple but beautiful buildings provided easy-to-operate methods for engaged occupants to control the natural forces around them to maintain indoor comfort.

* Note: Some of the research for the Kappe and VDL Garden House was developed for the exhibit "Technology and Environment: The Postwar House in Southern California" co-curated with Judith Sheine, Lauren Bricker, Philip Pregill, and Tim Sakamoto on display during the spring of 2013 at the Kellogg Gallery at Cal Poly Pomona University, partially supported by the Getty Foundation as part of the series Pacific Standard Time presents.

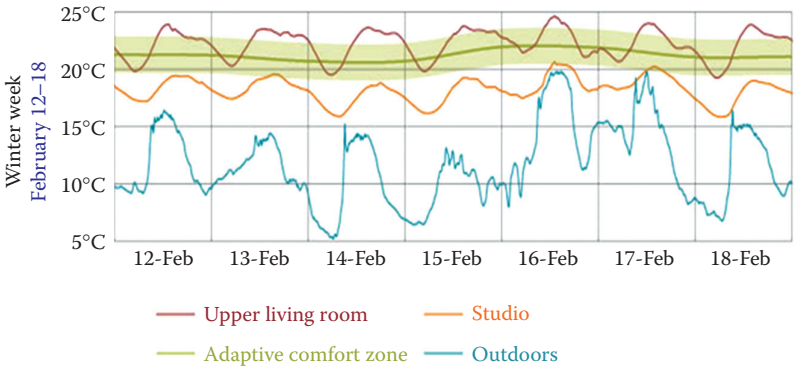


FIGURE 6.46 Summer temperatures Kappe house.

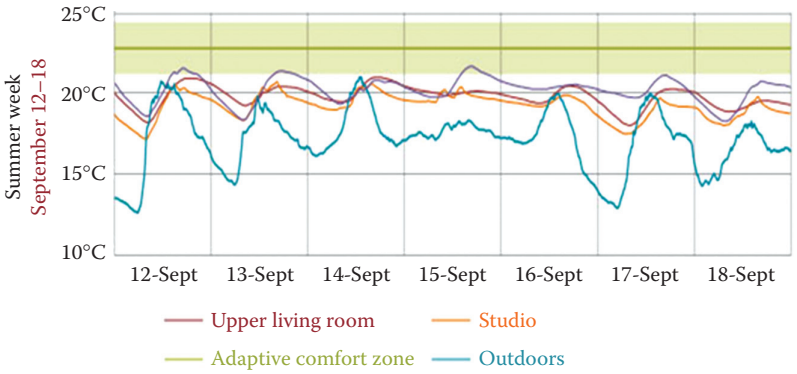


FIGURE 6.47 Winter temperatures Kappe house.

The strong relationship of most of the Case Study Houses with the environment established an implicit adaptation with the local climate introducing technological advances not present in typical buildings of the period. For example, most of the case study architects exploited available materials to their full technological potential and experimented with different construction techniques. Nevertheless, sustainability is not about imitation and nostalgia; it is about advancing design as it continues to evolve. So even though the Case Study Houses were innovative at one point, they are already obsolete in their use of materials and current green buildings include many technological advances not available at that time. However, many of the principles of the Case Study Houses are still valid and will probably continue to be valid for generations.

6.6.5 Vernacular Architecture in the Cold Climates

In cold climates, the main problem is the lack of heat (i.e., underheating), which causes excessive heat dissipation for all or most parts of the year. A climate-responsive building in a cold climate usually has an envelope that covers a large volume with a small amount of skin. This is one of the reasons that many vernacular buildings in cold climates are variations of domes, cylinder, or cubes, built with different materials. Insulation is usually provided by the thickness of the walls, which are generally built using local materials such as rock, earth, wood, or even snow. Windows are small to avoid heat losses, even though this also means reducing the amount of radiation and light entering the building. These buildings usually also have an internal heat source, such as a fireplace (Figure 6.48).

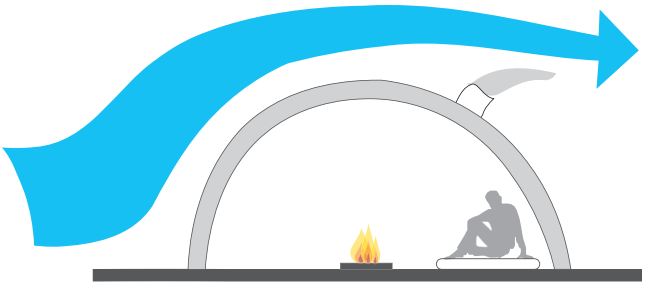


FIGURE 6.48 Cold climate archetype.

FIGURE 6.49 Vernacular building in the Andes Mountains in Venezuela.

There are many vernacular variations of buildings in cold climates. Figure 6.49 shows a vernacular building in the Venezuelan Andes Mountains. It is also compact with very few windows to the exterior. The exterior walls shelter from the cool outdoor winds, while a fireplace warms the interior of the space.

6.7 EFFECTS OF CLIMATE ON EMISSIONS

Vernacular buildings were not designed to operate with mechanical systems, and they used architectural features only to achieve comfort. However, many of these original vernacular typologies have also been modified over time due to changes in standard of living or cultural factors.

Energy used for operation of the building is the single most important source of emissions, and the intensity of these emissions is affected by the climate of the site and the building's program. To determine the effect of climate on energy emissions, the energy use of a single-family dwelling was calculated in these four climates. To better determine the effect of climate on emissions, emissions from construction, waste, water, and transportation were kept constant.

The house used in the simulations was two stories high and 14.6 m by 7.3 m (48 by 24 ft), with 214 m^2 (2300 ft^2) gross building floor area, similar to the U.S. average house in 2005. Climate files for the four previously discussed climate types were selected: (1) hot and dry, represented by California climate zone 15 (El Centro); (2) hot and humid, represented by Miami, Florida; (3) temperate, represented by California climate zone 6 (Los Angeles); and (4) cold, represented by California climate zone 16 (Bishop, CA). Emissions from operation changed as the heating, ventilating and air conditioning (HVAC) system used more or less energy to provide thermal comfort in the different climates.

6.7.1 Assumptions for Simulations

California Energy Code Title 24 (California Energy Efficiency Standards, 2008) was used to design the building envelope for all climate zones; package D for homes with natural gas was used. A gas furnace with an annual fuel utilization efficiency (AFUE) of 80% was used. The same envelope was used in the hot and humid zone as in the hot and dry climate zone (Table 6.1).

6.7.2 Operation

Operational emissions involve all the emissions produced from the energy used to keep the buildings and everything inside it running. According to Bordass (2006), the process to estimate CO_2 emissions generated from operation in buildings involves five steps:

1. Define the boundary of the premises. Boundaries should be where they make practical sense in terms of where the energy can be counted (e.g., the area fed by the meters) and how the area is run (a tenancy, a building, a site, or even a district or a city). One may look at more than one boundary: for a university, the campus, specific buildings, and individual departments; for a rented building, the whole building and each tenancy.
2. Measure the flows of each energy supply across the defined boundary. Normally this will be annual totals by fuel, though details of load profiles could sometimes be included.
3. Define carbon dioxide factors for each energy supply.
4. Multiply each energy flow by the appropriate carbon dioxide conversion factor to get the emissions associated with each fuel.
5. Add them up to obtain the annual total of CO_2 emissions.

TABLE 6.1
Envelope Characteristics

		Title 24 Package C				Title 24 Package D			
	Referenced City	Ceiling	Wood Frame Walls	Glazing *U*-Value	EGR (Glazing Max Area)	Ceiling	Wood Frame Walls	Glazing *U*-Value	EGR (Glazing Max Area)
California CZ 16 cold	Bishop	R49	R29	0.42	14%	R38	R21	0.55	20%
California CZ 15 hot and dry	El Centro	R49	R29	0.38	16%	R38	R21	0.55	20%
Miami hot and humid	Fresno	R49	R29	0.38	16%	R38	R19	0.57	20%
California CZ 6 temperate	Los Angeles	R38	R21	0.42	14%	R30	R13	0.57	20%

To calculate the CO_2 factors for each energy supply, the emission factors must be determined for each one. In the United States there are several methods to determine the conversion factor (Bryan and Trusty, 2008):

1. The U.S. Environmental Protection Agency (EPA) Power Profiler calculates CO_2 emission factors for historical yearly average emissions for every U.S. zip code.
2. The EPA eGRID is a database that has hourly CO_2 emissions for every U.S. power plant. However, these data are also historical, and it is a nontrivial task to estimate marginal generation from this database.
3. The National Renewable Energy Laboratory (NREL) model develops direct and indirect impacts for typical building fuels and uses CO_2e, which includes other important GHGs besides CO_2, like methane (CH_4) and nitrous oxide (N_2O). This model generates emission factors for all U.S. regions as well as the nation.
4. The CEC E3 model uses the output of a production simulation dispatch model to forecast average and marginal CO_2 emission factors for California.

Two programs, Home Energy Efficient Design (HEED) and DesignBuilder, were used to predict energy use in the four locations. HEED (Milne, 2007) is an energy analysis tool that calculates the building's performance. When the program is first launched, it asks four questions about the project (i.e., building type, square footage, number of stories, and climate location), and with this information it creates Scheme 1, a building that meets the California Energy Code. It then designs a second scheme that is usually about 30% better. Next, it suggests other strategies that designers can test using the remaining seven schemes. HEED makes it very easy for users to change any aspect of the building's design, and after each design change it shows how the building's performance compares with the initial schemes.

DesignBuilder is a user interface to the EnergyPlus dynamic thermal simulation engine. It features an Open Graphics Library (OpenGL) solid modeler, which allows building models to be assembled by positioning, stretching, and cutting blocks in three-dimensional (3D) space. Three-dimensional elements provide visual feedback of actual element thickness and room areas and volumes. Data templates allow users to load common building constructions, activities, HVAC, and lighting systems into the design by selecting from drop-down lists. These templates can also be added. Users can switch between "Model Edit View" and "Environmental Performance Data," which is displayed without needing to run external modules and import data.

The yearly energy used by the building as determined with these programs is multiplied by a conversion factor to determine GHG emissions. Because different locations use different utilities at different times, which would further muddle the numbers, the same conversion factors were used for electricity and gas in all the climates: 0.62 kg of CO_2 per kWh for electricity, which is the average value for the United States (eGRID, 2007); and 0.19 kg per kWh (5.43 kg of CO_2 per therm) for natural gas, which is the value proposed by DEFRA (2005).

6.7.3 Construction

Even though most of a building's emissions originate from its operation, carbon neutrality is more than just the operation of the building and includes the building's life cycle, from fabrication to demolition. GHG emissions from construction processes are usually related to the embodied energy in the building and can be generated in three different distinct stages: (1) during the fabrication of the materials used in the building; (2) during transportation of materials to the building; and (3) during construction of the building. Materials that need more energy to produce, such as steel, aluminum, and cement, are responsible for more emissions than materials like stone or wood. Local materials also usually produce fewer emissions than materials that have to be

transported from longer distances. The construction process affects the embodied emissions, and an efficient, streamlined semiprefabricated system will produce fewer emissions than an inefficient construction process.

Emissions for construction were calculated using buildcarbonneutral, a very simple calculator that provides rough results. The total emissions from construction were 53 metric tons of CO_2/year (116,812 lbs/yr). A building life of 50 years was assumed, which is equivalent to 1061 kg/yr of CO_2e (2336.2 lbs/yr) over the life of the building, and this same number was used in all sites. If construction components could be recycled or the life of the building was extended, then the impact would be lower. If the building required major renovations, then construction-related emissions would be higher. More precise data can be generated using Athena EcoCalculator for assemblies. However, this calculator does not provide results for all regions. Results from buildcarbonneutral are not precise, and even though the imprecision could be quite substantial, the results can provide a preliminary idea of construction-related emissions.

6.7.4 Waste

Waste generated from the building must also be treated. More waste requires more treatment and can generate methane, which is a potent GHG produced in landfills. To figure out these emissions, the waste section of the carbon emissions calculator developed by the EPA was used (EPA, 2009). Even though many cities and households recycle, it is still not mandatory in many regions of the United States, so for these calculations I did not assume that the household recycled. According to this calculator, emissions from waste for a family of four would be 1856 kg CO_2e, and if recycling was implemented (e.g., plastic, aluminum, newspapers, glass, and magazines), emissions would be reduced to 1044 kg CO_2e. If more recycling and composting were introduced, emissions would be reduced even more.

6.7.5 Water

The process used to treat the water provided to the building and coming out of the building usually is also responsible for the generation of GHG emissions. The water used in the building must be pumped from the source, then treated to be made potable, and then pumped to the building for consumption. The wastewater from the building must also be treated, which also generates carbon emissions, indirectly by using energy for these processes and directly by releasing methane.

A study on water-related energy use in California (Commission on Energy, Water and Parks, 2007) calculated the embedded energy in water for Southern and Northern California. The study estimated the amount of energy needed for each sector of the water-use cycle in terms of the number of kilowatt-hours (kWh) needed to collect, extract, convey, treat, and distribute 1 million gallons (MG) of water and the number of kWh needed to treat and dispose of the same quantity of wastewater. For Southern California, the embedded energy per MG was estimated to be 13,021 kWh. To provide 552,670 L (146,000 gal) of water per year to a family of four in Southern California requires 1901 kWh. If every kWh of electricity in California generates about 0.32 kg (0.7 lbs) of CO_2, then a family of four generates about 605 kg (1331 lbs) of CO_2/year, which is equivalent to 0.0034 kg of CO_2/L. Again, to simplify, this number was used for all sites even though the number for Southern California is probably higher than in the rest of the United States.

6.7.6 Transportation

By its location, a building is also indirectly responsible for CO_2 emissions from transportation because it affects how building users move to and from the building. A location close to public transit lines or in urban areas with higher density and walkable neighborhoods usually reduces transportation-related carbon emissions. For this analysis, emissions from transportation were not included.

6.7.7 Carbon Emissions in the Four Climates

In the cold climate, the average emissions from operational energy are 6050 kg of CO_2e, which is 69% of the total emissions (Table 6.2). To determine the impact of the different sources of operational energy, a more detailed analysis including heating, cooling, fans and blowers, appliances, water heaters, and lighting was performed. This analysis indicates that in the cold climate, after averaging the results from HEED and DesignBuilder, most of the emissions from operational energy are produced by space heating. DesignBuilder indicates a need for more cooling during many midseason days than HEED.

Emissions from operation are a smaller proportion of all emissions in the temperate climate, averaging 3857 kg of CO_2e (59% of the total). Heating and cooling make up a smaller portion of the total, and water heating and lighting become more important factors.

Operational energy in the hot and dry climate accounts for 5807 kg of CO_2e, which is a large portion of total emissions (68%). Most of these emissions (41%) are from cooling, plus 8% for fans and blowers.

Operational energy in the hot and humid climate accounts for 5052 kg of CO_2e, or 65% of the total building emissions. Most of the emissions from operational energy in a hot and dry climate are from cooling (40%), plus 7% for fans and blowers, which are part of the HVAC system.

In this reference house, operation is the single largest source of emissions (Table 6.2) and the contributor with the highest percentage. Emissions from operation are highest in the cold climate, followed closely by the warm climates, and are lowest in the temperate climate (Figure 6.50). Total emissions are also higher in the cold climate (8768 kg CO_2e/yr), followed by the hot and dry climate (8539) and the hot and humid climate (8148). The lowest value is 6537 in the temperate climate, demonstrating the impact that heating and cooling have on total emissions. Looking into the emissions from operation, emissions from heating and cooling vary by climate but are usually the most important contributor (Figure 6.51). Of course, heating is a larger contributor in a cold climate and cooling in a warm climate.

Operation is the largest source of emissions in all climates and is most significant in the cold climate (69%) and least significant in the temperate climate (59%). The emissions from heating constitute the most significant factor in the cold climate (37%), whereas cooling is the most significant in the hot and dry climate (41%) and in the hot and humid (40%) climate. In the temperate climate, cooling and lights (19%) are more significant than heating and cooling. Appliances are also a significant percentage of emissions in the temperate climate. For heating, a gas furnace is used; if electricity was used for heating, it would have a larger proportion of the total. Also, the role of appliances might be underestimated; data can be modified in the simulations to include more energy use from appliances in our ever more wired homes.

TABLE 6.2
Source of CO_2 Emissions in Different Climates

	Climate			
Emissions (lbs CO_2)	**Cold**	**Temperate**	**Hot and Dry**	**Hot and Humid**
Operational	69	59	68	65
Construction	12	16	12	14
Waste	12	16	12	13
Water	7	9	7	8
Total	100	100	100	100

Note: Construction, waste, and water are constant, and transportation is not included. All numbers in percent.

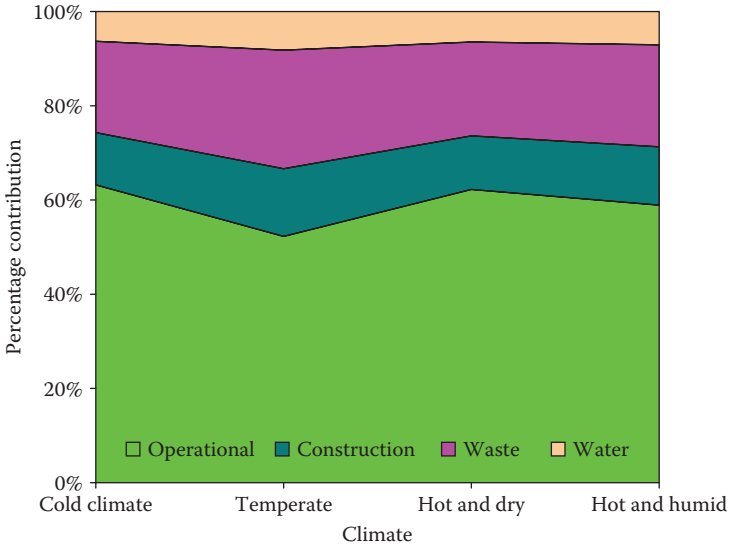


FIGURE 6.50 Effect of climate in emissions from operation (construction, waste and water are constant).

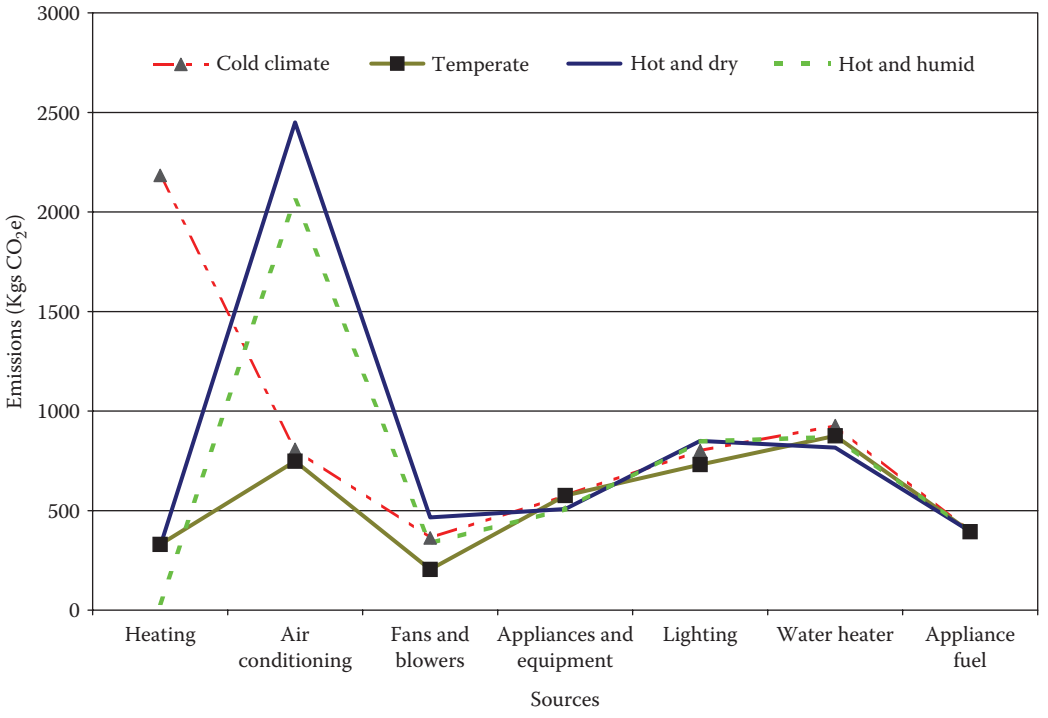


FIGURE 6.51 Effect of climate on source emissions from operational energy (Averaged from HEED and Design Builder).

Because operational energy, which includes heating and cooling, has the most impact on emissions, addressing it should be a priority. This can be accomplished with energy efficiency strategies and good old-fashioned passive solar. Photovoltaic and wind systems can also reduce operational emissions by providing clean energy. However, other strategies that affect emissions from construction, water, and waste must also be implemented. These include living close to work, working at home, recycling, and reducing water consumption. Implementing these design strategies (better envelope, more efficient HVAC system, and passive strategies) can dramatically reduce emissions in a typical home in all climates.

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7 Solar Geometry

The sun is the source of all life on our planet. It is a huge fusion reactor that works by merging lighter atoms into heavier atoms (hydrogen into helium). This can happen only with the very high temperatures and pressure that are in the nucleus of the sun. By weight, the sun is 70% hydrogen, 28% helium, 0.5% carbon, 0.5% nitrogen, 0.5% oxygen, and 0.5% other elements.

Because the earth is tilted at a fixed axis of about 23.5 degrees, the northern hemisphere faces the sun in June and the southern hemisphere faces the sun in December. On the northern hemisphere's summer solstice around June 21, the sun's rays will be perpendicular to the earth's surface along the Tropic of Cancer. This is the longest day in the northern hemisphere and the shortest in the southern hemisphere. Around December 21 the situation is reversed, and this is the shortest day of the year in the northern hemisphere and the longest in the southern hemisphere (Figure 7.1).

The temperature of the air and land is mostly a result of the effect of the solar radiation absorbed by the land or the water, which then heats or cools the air above it. As latitude (LAT) increases, winter occurs because the days are shorter with a corresponding reduction in the amount of daylight and solar radiation. Another factor is that in the winter the sun is lower in the sky and its intensity is spread over a larger surface. This is called the cosine effect and is explained graphically in Figure 7.2.

Slopes also affect the amount of radiation falling on a surface. If the angle of the slope is perpendicular to the sun's rays, as in a south-facing slope in the northern hemisphere (A), it will receive more solar radiation than a flat surface (B) (Figure 7.3). A surface facing away from the sun will also receive less solar radiation, which is the case of a north-facing slope in the northern hemisphere. There can be significant temperature differences between a north-facing and a south-facing slope in the same climate. Trees can also block solar radiation and reduce the amount of radiation that is reaching a surface (Figure 7.4).

7.1 THE SUN IN THE SKY VAULT

Several concepts can help in locating the sun in the sky vault: solar declination (DEC), hour angle (HRA), solar altitude (ALT), and solar azimuth (AZI).

7.1.1 Solar Declination and Hour Angle

The earth's axis of rotation is not perpendicular to the sun/earth plane; it is tilted 23.5 degrees. This causes the North Pole to tilt toward or away from the sun, depending on where the earth is in its orbit around the sun. The solar declination is the angle between the sun's rays and earth's equatorial plane, or the angle between the earth–sun vector and the equatorial plane. It is the angle between the zenith at the equator and the position of the sun at noon on a given day and varies ±23.5 degrees on a given year. The total vertical travel between winter and summer is 47 degrees or ±23.5 degrees (Figure 7.5).

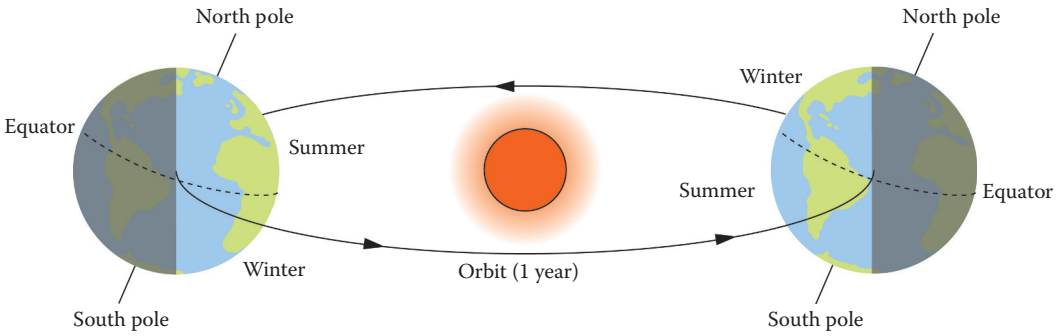


FIGURE 7.1 Earth's rotation around the sun with annual variation.

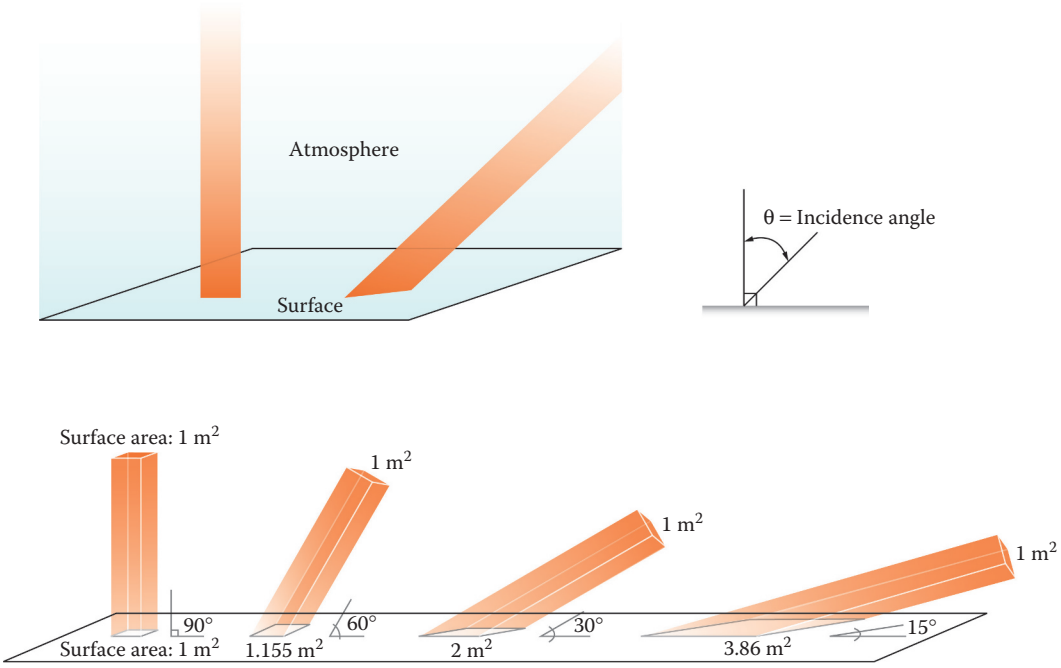


FIGURE 7.2 Effect of the angle of incidence on solar radiation on a surface.

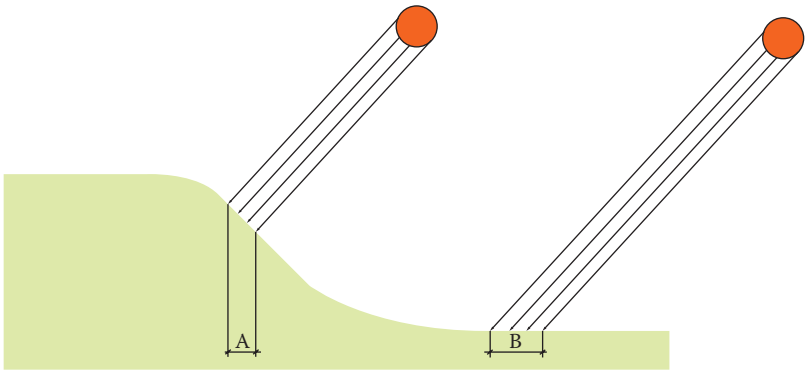


FIGURE 7.3 Effect of the slop on the amount of incident solar radiation.

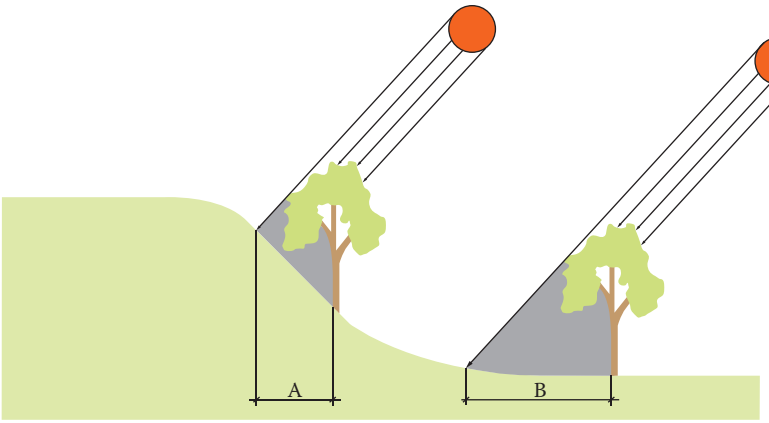


FIGURE 7.4 Effect of trees on solar radiation.

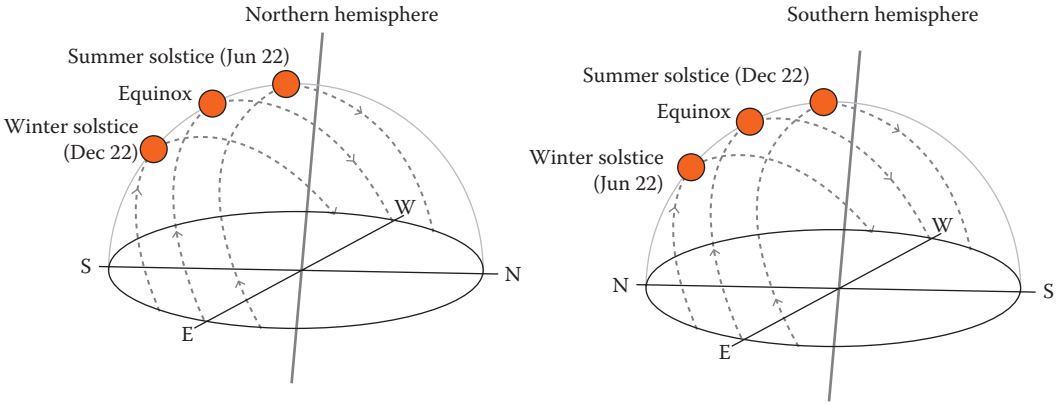


FIGURE 7.5 Variation of solar position in the sky.

HRA is the Solar Hour Angle, defined as the number of hours between the solar noon and the time multiplied by the constant 15/h (the sun moves 15 degrees per hour). Solar time is used in these calculations.

7.1.2 Solar Azimuth and Altitude

The position of the sun in the sky at any given moment can be determined by two values: the solar altitude and the solar azimuth. These are plotted in an imaginary celestial sphere or sky dome in which we are in the center (lococentric view). We regard the radius of this sphere to be infinite, and we can see only 1/2 of the celestial sphere at any time. The boundary between the visible and invisible portions of the celestial sphere is called the horizon. The poles of the horizon—the points directly overhead and underneath—are called the zenith and the nadir, respectively.

The solar altitude describes the vertical angle at which the sun's rays strike the earth and tells us how high the sun is in the sky (Figures 7. 6 and 7.7). It is an angle between the sun and the horizon and is a function of the geographic latitude, time of year, and time of day. The altitude of the sun is zero when it is at the horizon, at sunrise or sunset, and 90 degrees when it is straight up and vertical above the observer.

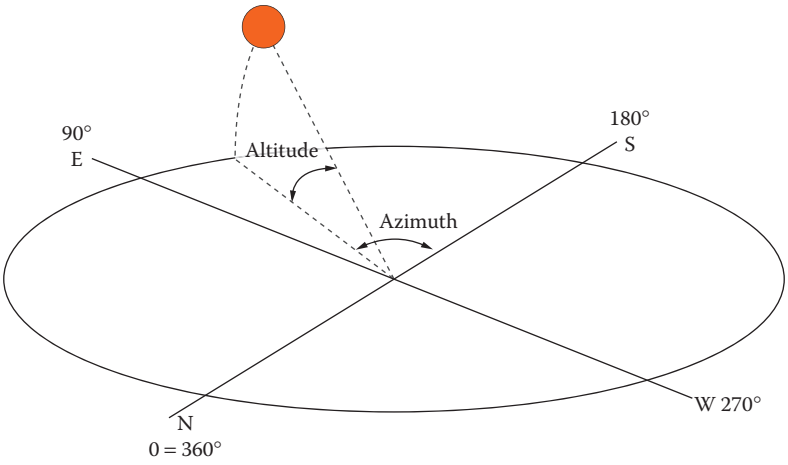


FIGURE 7.6 Solar position angles: altitude and azimuth, in the international system.

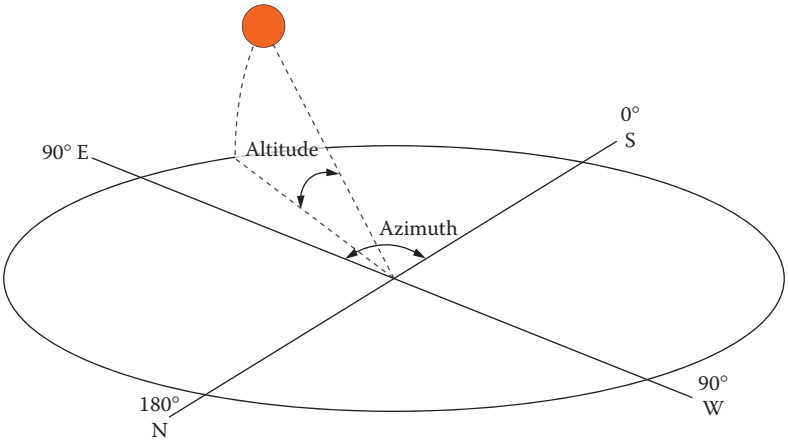


FIGURE 7.7 Solar position angles: altitude and azimuth, in the U.S. system.

The altitude can be determined using the following equation

$$\text{ALT} = \arcsin(\sin \text{DEC} \times \sin \text{LAT} + \cos \text{DEC} \times \cos \text{LAT} \times \cos \text{HRA}) \quad (7.1)$$

where:

DEC is declination and measures the variation in the position of the sun on a seasonal basis
LAT is latitude for the site
HRA is the Solar Hour Angle

The solar altitude at a given location can change dramatically between summer and winter. At solar noon on equinox days, the altitude of the sun is equal to 90 degrees minus the latitude at the site. On solstice days, it is equal to the altitude at the equinox plus or minus the earth's declination. In the northern hemisphere, it is higher in June and lower in December, and in the southern hemisphere it is higher in December and lower in June.

The solar azimuth is the direction of the sun measured in the horizontal plane from the north in a clockwise direction starting from the north; zero degrees is the north position,

90 degrees is east, 180 degrees is south, and 270 degrees is west (Figures 7.6 and 7.7). In the United States, the azimuth is measured from the south and –90 degrees is used for east, and +90 degrees for west (Figure 7.7). The solar azimuth is also called the bearing angle and can be determined using.

$$\mathrm{AZI} = \arccos\left[\frac{(\cos \mathrm{LAT} \times \sin \mathrm{DEC} - \cos \mathrm{DEC} \times \sin \mathrm{LAT} \times \cos \mathrm{HRA})}{\cos \mathrm{LAT}}\right] \tag{7.2}$$

where:

DEC is declination
LAT is latitude for the site
HRA is the Solar Hour Angle
ALT is the altitude of the sun

7.2 SOLAR CHARTS

The position of the sun in the sky varies during the day and during the year and is a function of the latitude. Complete understanding of solar positioning is necessary for accurate solar design and reasonable climatic response. Solar position can be determined using the previous equations, in fact these or similar equations are used by most software to calculate shadows or to generate sun path charts. It is usually easier to read the sun's position from a table, software that uses the equations, or off a sun path diagram, which can be generated for any given latitude and longitude than to use the equations.

There are several ways to plot the three-dimensional celestial hemisphere on a two-dimensional surface. The vertical sun path diagram is generated by vertical projections of the sky dome, and the horizontal sun path diagram is generated by horizontal projections from the sky dome (Figure 7.8).

7.2.1 Vertical Sun Path Diagram

A vertical sun path diagram uses a cylindrical projection system to project the hemisphere onto a cylindrical vertical surface around it, similar to the earth maps made with a Mercator projection from the earth's globe. A vertical sun path diagram has the same problem as those maps and provides an accurate representation close to the equator, but it produces a distorted image closer to the poles, in this case the zenith. The distortion increases because the zenith, which is just a point, is stretched in this map into a line that has the same length as the horizon circle. Figure 7.9 shows a vertical sun path diagram for 34° north latitude.

Traditionally these sun charts would be used by designers from appendixes in books and generated for different latitudes in increments of maybe 10 or 15 degrees; however, it is now possible to generate them automatically using multiple software. (e.g., Climate Consultant for vertical sun path diagrams).

7.2.2 Horizontal Sun Path Diagram

There are several methods to plot the sky vault in a two-dimensional horizontal sun path diagram. In an equidistant representation system, the altitude is plotted as a set of radial coordinates with evenly spaced altitude circles. In an orthographic projection, the altitude lines are plotted closer together as they approach the horizon because the sky vault is more vertical at lower altitudes and the point's project closer to each other, producing distortion toward the horizon. The stereographic projection uses the theoretical nadir point, which is located opposite the zenith, as the center of the projection. Figure 7.10 shows a horizontal sun path diagram for 34° north latitude, and Figure 7.11 schematically shows horizontal sun path diagrams for different latitudes. The effect of the latitude

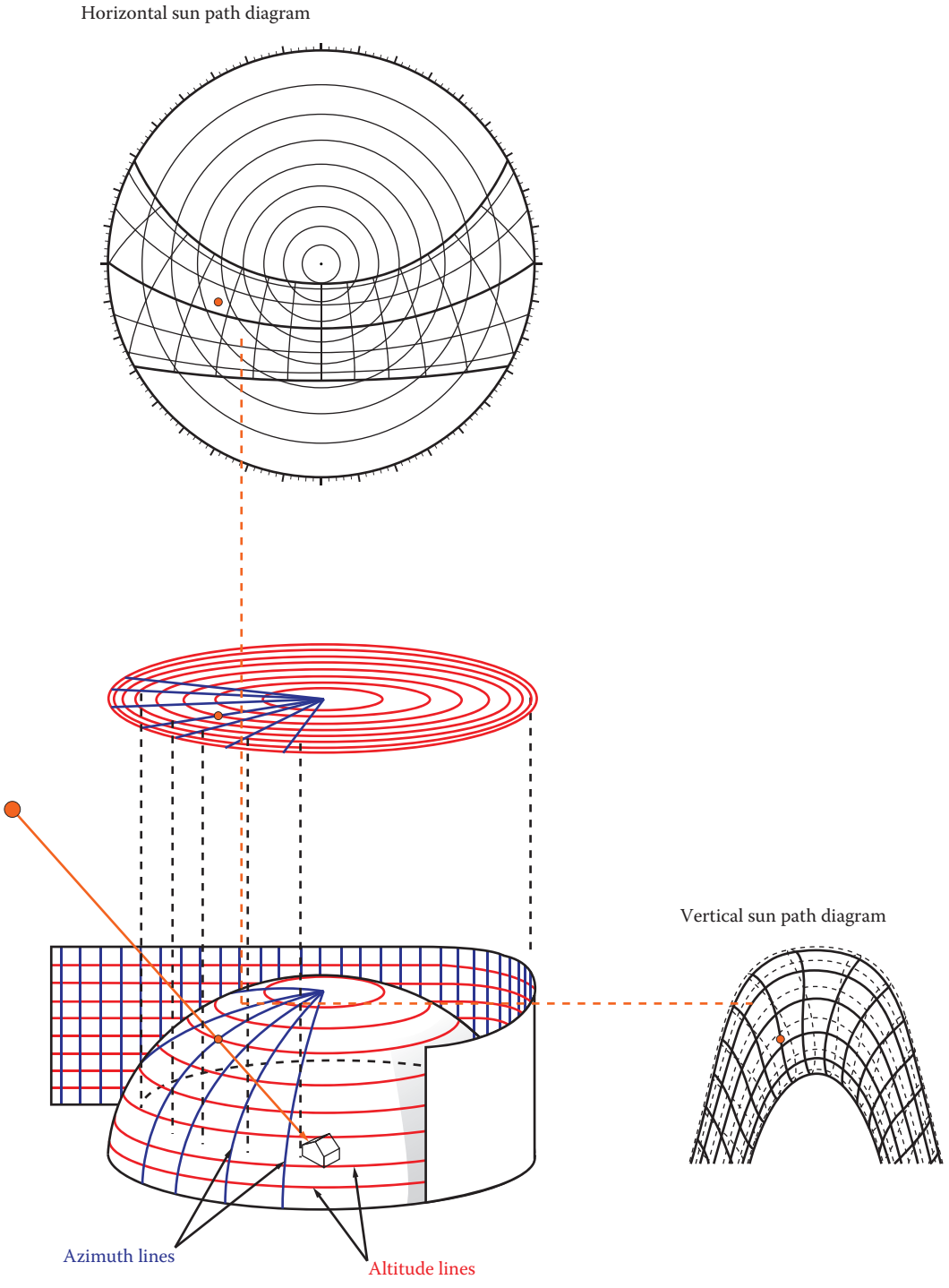


FIGURE 7.8 Projection of the vertical and horizontal sun path diagrams.

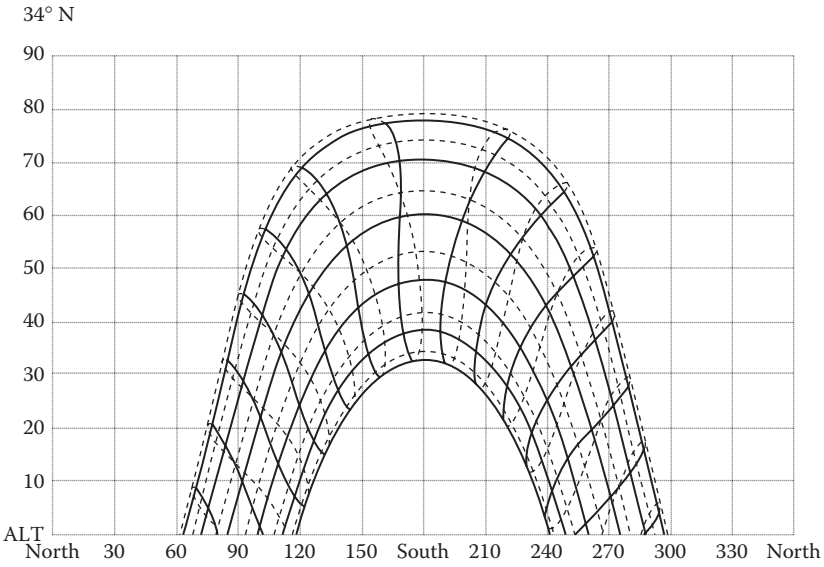


FIGURE 7.9 Vertical sun path diagram for 34° north latitude.

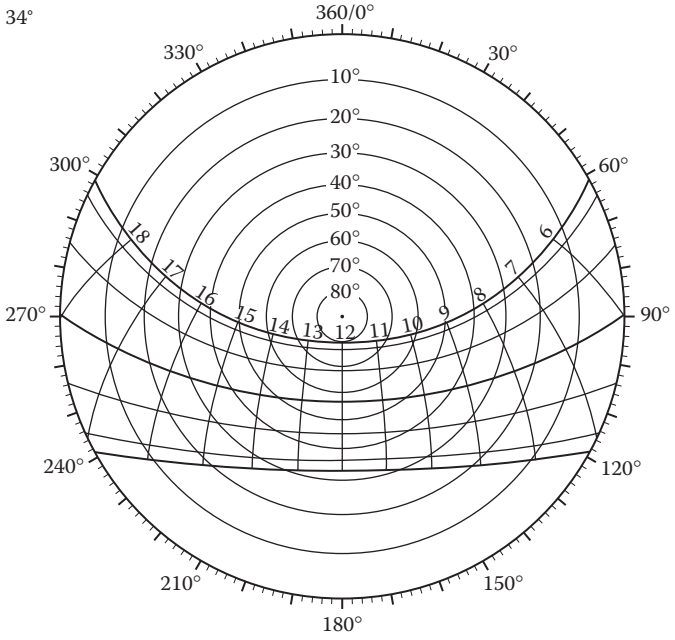


FIGURE 7.10 Horizontal sun path diagram for 34° north latitude.

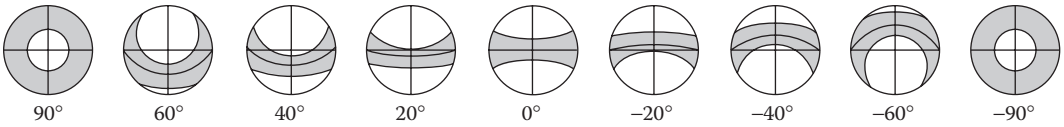


FIGURE 7.11 Schematic horizontal sun path diagrams for different latitudes.

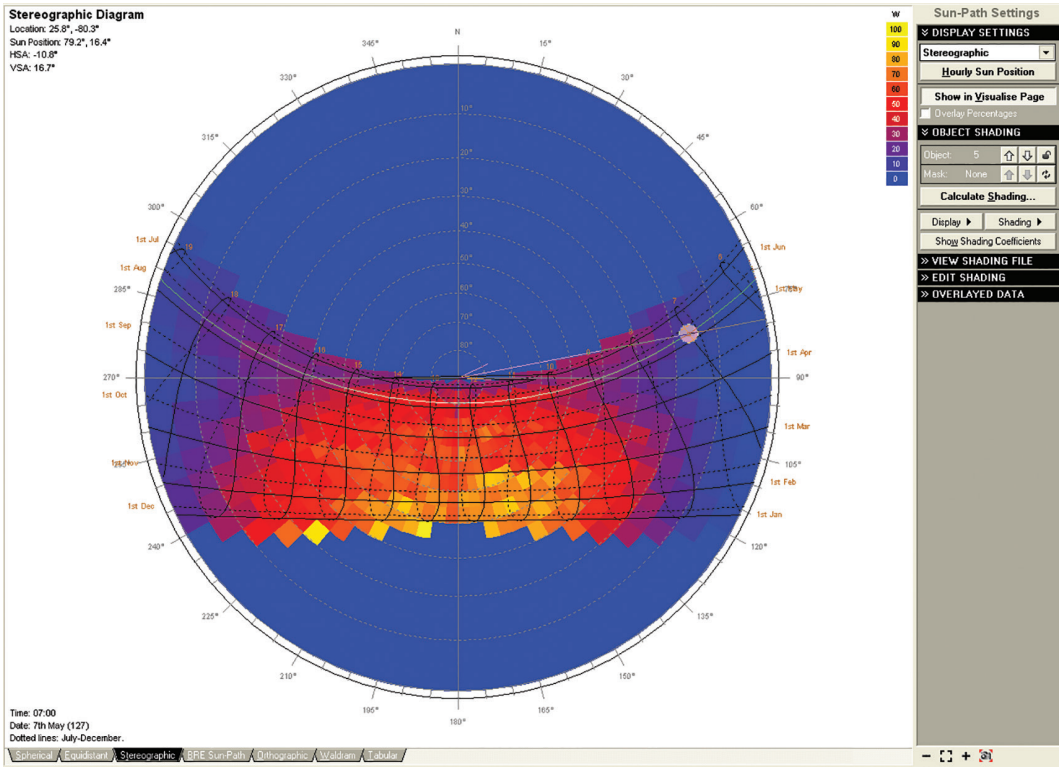


FIGURE 7.12 Example of horizontal path diagram with superimposed radiation data generated with Ecotect.

is very clear on the sun path. While the sun's path is symmetrical along an east west line close to the equator and the sun rises quickly close to the east and sets close to the west, as we move away from the equator it is more asymmetrical with lower altitude sun in the winter and higher altitude sun in the summer.

It is now possible to use software such as Ecotect to superimpose solar radiation data on a horizontal sun path diagram indicating the amount of solar radiation coming from the sun at specific hours and days (Figure 7.12) for specific locations, providing additional information to be used in the design of shading systems.

7.3 SHADING THE BUILDING

Heat flows through a window by conduction, convection, and radiation and can be a very important part of heat gains and losses in a building. These processes will be discussed in more detail in Chapter 6; however, in general heat losses in the winter are by conduction, radiation, and infiltration, and heat gains are by radiation. Heat gains and losses in the summer can be by conduction, radiation, or ventilation. A shading system should provide shade when it is necessary to block solar radiation (overheated period) and should allow solar radiation when it is necessary to heat the building (under-heated period).

For appropriate shading, it is very important to determine the overheated and underheated periods. There are several methods to determine the overheated period: (a) based on exterior temperature, (b) based on degree days, or (c) using an energy model. The goal of all of these methods is to predict when solar gains will increase cooling loads and shades will be needed most. Chapter 11 describes the process using an energy model, while the graphical method described in this chapter is based on the method developed by the Olgyay brothers before computer simulation programs were available. Even though using an energy model provides more precision, not everybody has access to energy simulation tools and the graphical method can be implemented manually or with free software such as "Climate Consultant." All of these methods utilize solar geometry and climate data to provide results. Energy models also consider the effects of internal gains and envelope materials. In all methods, the goal is to estimate as best as possible the periods (months and hours) during which shading will be required so that it is implemented only when needed.

It is possible to shade the windows with external or internal shading devices or using the glass pane itself. Each of these has advantages and disadvantages. An external shading system has the advantage of blocking the solar radiation before it penetrates the building so more heat stays outside, but it has the disadvantage of increased maintenance due to exposure to the climatic elements. Fixed external shading systems are usually classified as horizontal, vertical, or combined (egg crate) and can of course be designed in many different sizes and variations. Solar geometry is used to design them; they should not be so large that they block too much daylight or so small that they do not provide sufficient protection when it is needed. The fact that yearly temperatures are not symmetrical around solar geometry further complicates the design of fixed external systems.

External shading devices can also be operable permitting to more precisely adjust to different solar positions, during different times of the year, and better responding to the dynamic nature of weather, which does not always correlate with the seasons. The position of these movable devices can also be adjusted as a function of indoor and outdoor temperature instead of only the solar position as the fixed shading devices (Figure 7.13). These devices are constrained only by the designer's imagination and the fact that the device must block solar radiation.

Internal shading systems are usually operable and provide more flexibility to adjust to rapidly changing outdoor conditions. There are also many types of internal shading systems, which can be horizontal or vertical and include common systems such as horizontal blinds, louvers, shades, and curtains. Horizontal blinds are probably the most effective because they are very adjustable and flexible and can be completely closed to block all solar radiation or can be adjusted to specific angles to permit varying degrees of direct solar radiation or daylight. A reasonable solution is usually to design exterior systems to provide basic solar protection, while operable interior systems provide fine tuning options.

Some new high-performance glazing systems have fixed or operable blinds between the panes of glass. Other windows are electrochromic, which means they can be darkened or lightened electronically. A small voltage applied to the windows darkens them, and reversing

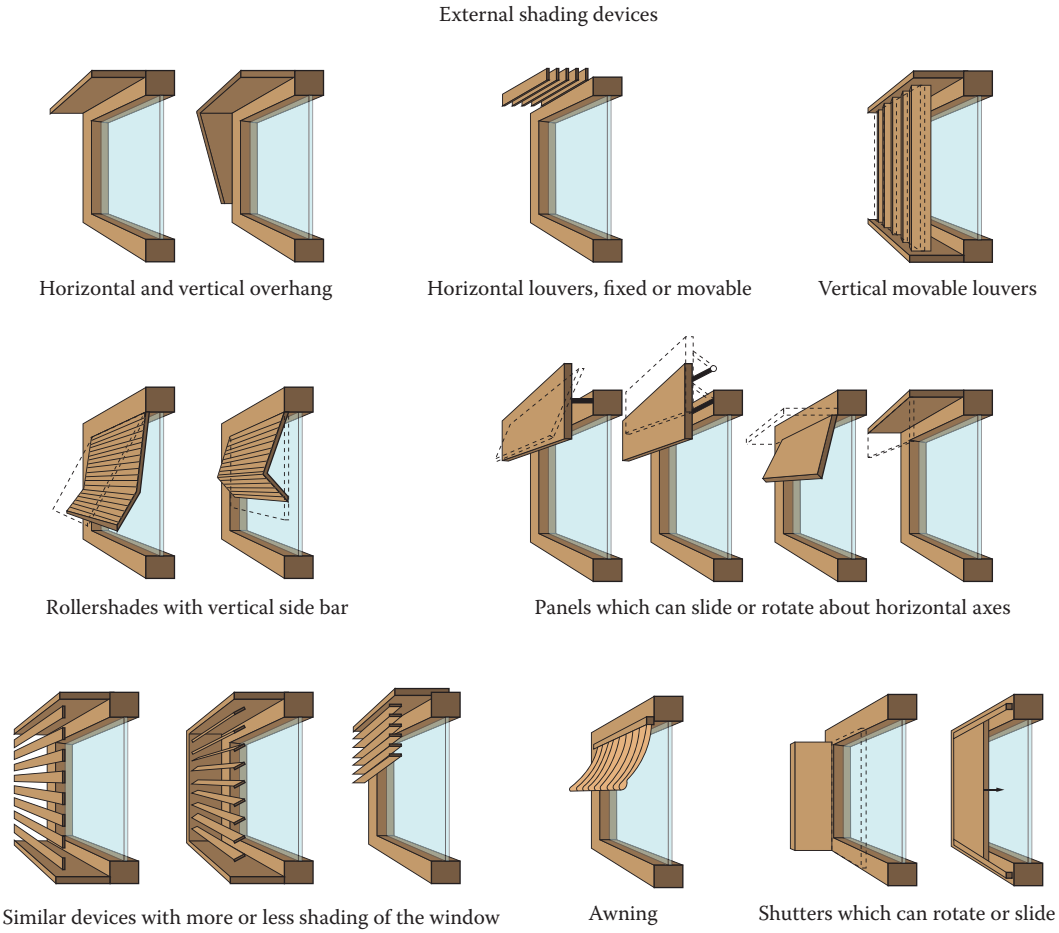


FIGURE 7.13 Examples of internal shading devices. (From Lewis, O., *A Green Vitruvius: Principles and Practice of Sustainable Architectural Design*, 2nd ed., James and James, London, 2001.)

the voltage lightens them, permitting the amount of light and heat that passes through the windows to be controlled, thus improving their performance compared with a transparent window.

7.4 DESIGN OF THE SHADING SYSTEM

Solar radiation entering through windows can contribute a significant amount of heat into the building, which can be beneficial when heating is required but can also be a liability when cooling is needed. Daylighting, however, should usually be provided during the whole year. A good shading system will provide solar protection during overheated periods and allow solar radiation during under-heated periods while providing daylight during the whole year.

Shadow angles describe the sun's position in relation to a building face of a given orientation (ORI) and can be used to describe the performance of the shading device or to specify a device by the type of shadow produced. Two shadow angles help us design an efficient shading system for each latitude and orientation: (1) the horizontal shadow angle (HSA; bearing angle); and (2) the vertical shadow angle (VSA; profile angle).

7.4.1 Horizontal Shadow Angle

The horizontal shadow angle is the difference in azimuth between the sun's position and the orientation of the building face (Figures 7.14 and 7.15). A smaller HSA angle means a larger fin. The horizontal shadow angle can be calculated using the following equation:

$$\text{HSA} = \text{AZI} - \text{ORI} \tag{7.3}$$

where:

HSA is the Horizontal Shadow Angle
AZI is the azimuth of the sun
ORI is the orientation of the façade, or the direction it is facing

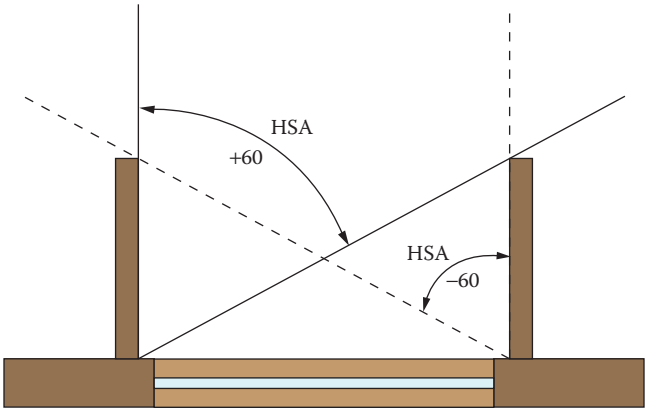


FIGURE 7.14 The horizontal shadow angle in plain view.

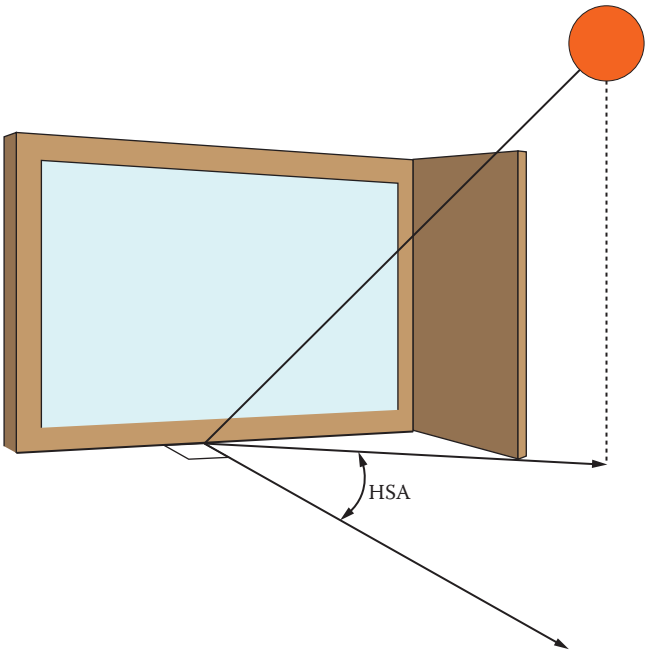


FIGURE 7.15 The horizontal shadow angle in 3D view.

HSA is positive when the sun is clockwise from the orientation and negative when it is counterclockwise. When the HSA is between the absolute values of 90 and 270, the sun is behind the elevation.

7.4.2 Vertical Shadow Angle

The vertical shadow angle, or profile angle, is the altitude of the sun projected to a plane perpendicular to the building face and measured in this same surface (Figures 7.16 and 7.17). When the sun

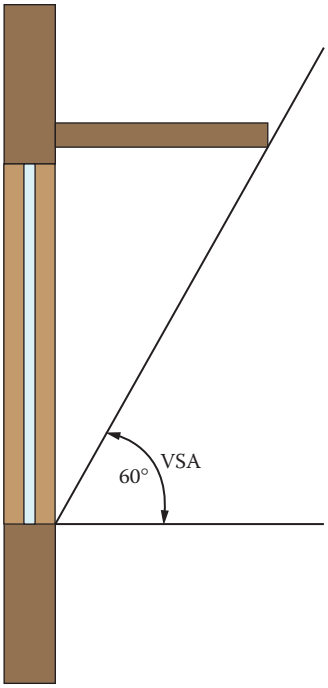


FIGURE 7.16 The vertical shadow angle in section view.

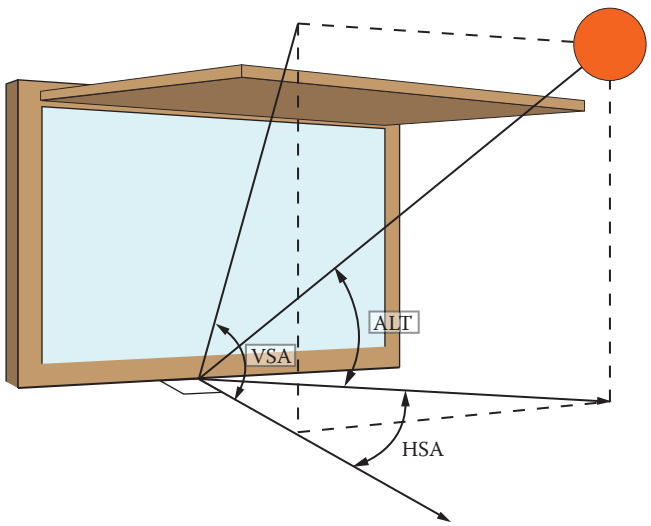


FIGURE 7.17 The vertical shadow angle in 3D view.

is parallel to the normal of the surface, then the solar altitude is equal to the vertical shadow angle. In any other case, when the sun is not perpendicular to the elevation, its altitude angle is projected parallel to the building face onto the perpendicular plane, and the VSA will be larger than the ALT. A lower VSA angle means a larger overhang. The vertical shadow angle can be calculated by

$$\mathrm{VSA} = \arctan\left(\frac{\tan \mathrm{ALT}}{\cos \mathrm{HSA}}\right) \tag{7.4}$$

where:
VSA is the Horizontal Shadow Angle
ALT is the altitude of the sun
HSA is the horizontal shadow angle

7.4.3 Shadow Angle Protractor

The shadow angle protractor is a semicircular protractor with two sets of lines that are used to calculate the horizontal and vertical shadow angles (Figure 7.18). The protractor has radial lines marked 0° at the center, –90° to the left, and +90° to the right, which give readings of the HSA. It has arcual lines that coincide with the altitude circles along the center line but then deviate and converge at the two corners of the protractor and give readings of the VSA. It is important to understand that these arcual lines are the vertical shadow angles and not solar altitude angles. The shadow angle protractor is used with the sun path diagram to determine the ideal vertical and horizontal shadow angles. As previously explained, it is important that the overhang be designed to the optimum dimension—not too large and not too small. If it is too large, unnecessary material is being used, blocking more daylight and creating darker interior spaces, which might be too cold if heating is needed in the winter or might need more heating. If the shading system is too small, it will not provide sufficient shade during the overheated period, making the space more uncomfortable or requiring more cooling energy.

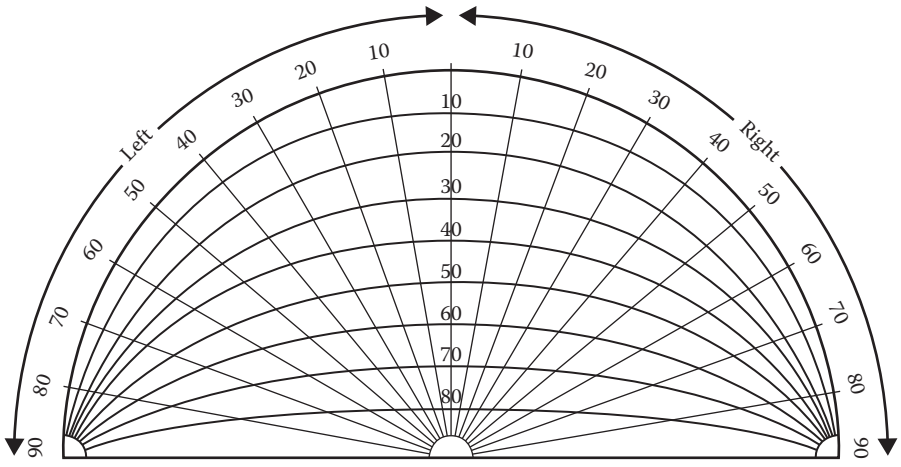


FIGURE 7.18 The shadow angle protractor.

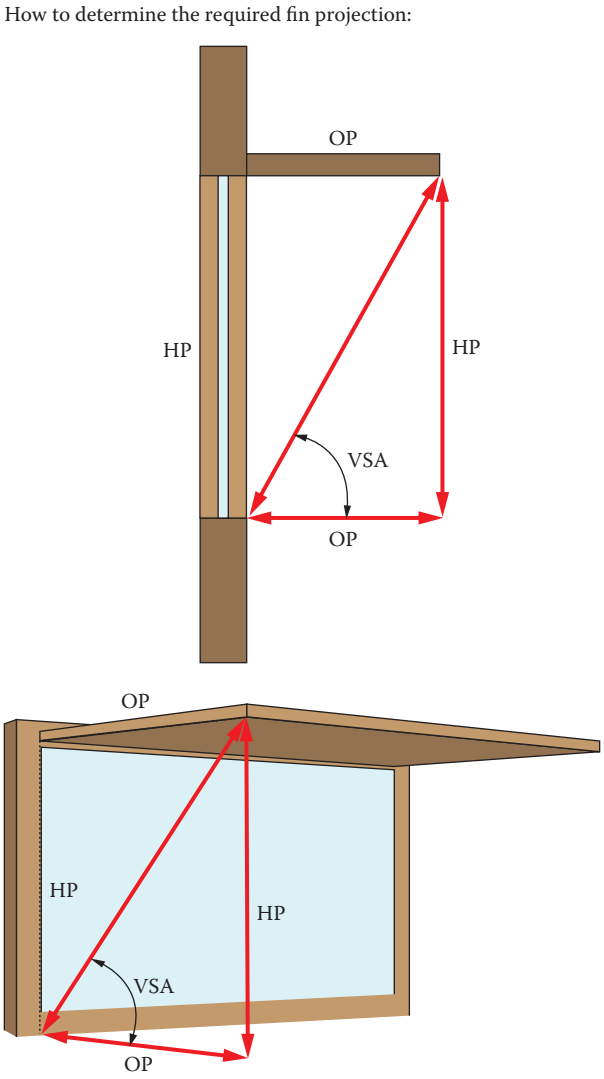


FIGURE 7.19 Calculating horizontal shading using VSA.

The following equation can be used to calculate the appropriate dimension for a horizontal element such as an overhang (Figure 7.19):

$$\mathrm{OP} = \frac{\mathrm{HP}}{\tan \mathrm{VSA}} \tag{7.5}$$

where:

OP is the horizontal overhang projection

HP is the height of the horizontal overhang height—the distance from the shading element to the bottom of the window, or the vertical distance that must be covered by the shadow produced by the overhang. If the overhang is above the window then that distance must be included also. If the overhang is sloped, HP is measured from the tip of the overhang

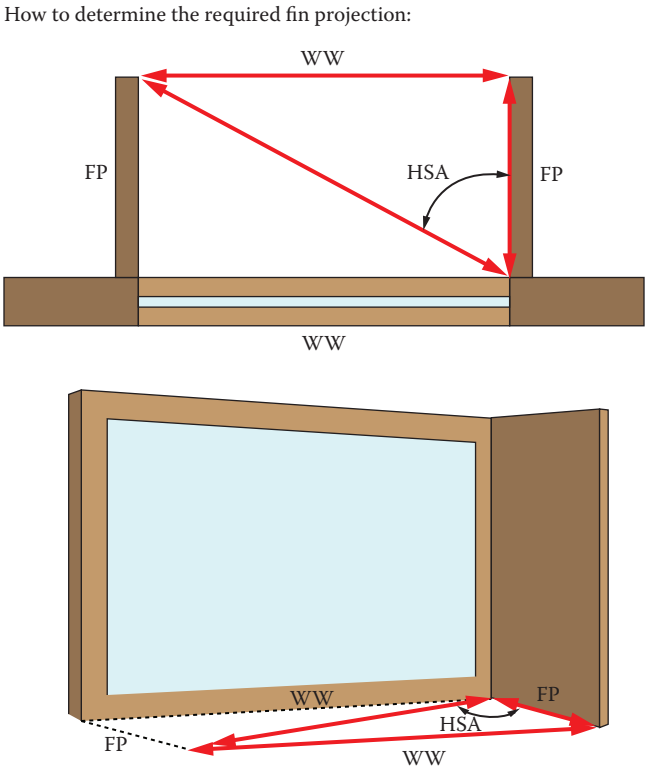


FIGURE 7.20 Calculating vertical shading using HSA.

The following equation can be used to calculate the appropriate dimension for a vertical element such as a fin (Figure 7.20):

$$FP = \frac{WW}{\tan HSA} \tag{7.6}$$

where:

FP is the Fin Projection of the construction element, or the fin size

WW is Window Width, or the width of the window that must be protected by the shadow of the fin

7.4.4 Example Design Process to Shade a South-Facing Window

As an example of this process, consider a designer who must shade a south-facing window (2 m high and 2 m wide) in Los Angeles during the overheated period, which can be determined with the appropriate weather file. If the method used is based on external temperature, Climate Consultant generates a vertical sun path diagram in which the temperatures are plotted with the different solar positions permitting to determine overheated and under-heated periods when shading is needed. Figures 7.21 and 7.22 show a vertical sun path diagram with temperatures, from June to December in Los Angeles, showing that most of the overheated hours are between 9 and 3 p.m. from June to September (Figure 7.22). There are overheated hours outside this area, but it is probably not cost-effective to design a shading system for all of these hours. These are usually better controlled with operable internal blinds.

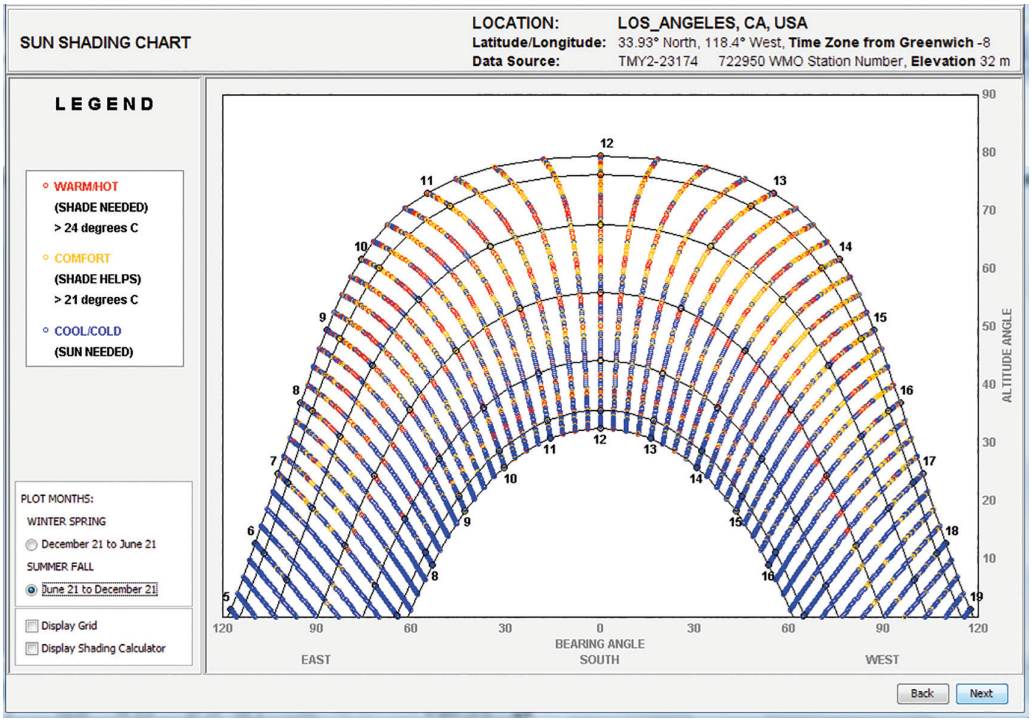


FIGURE 7.21 Vertical sun path diagram with temperatures for Los Angeles. (June to December.)

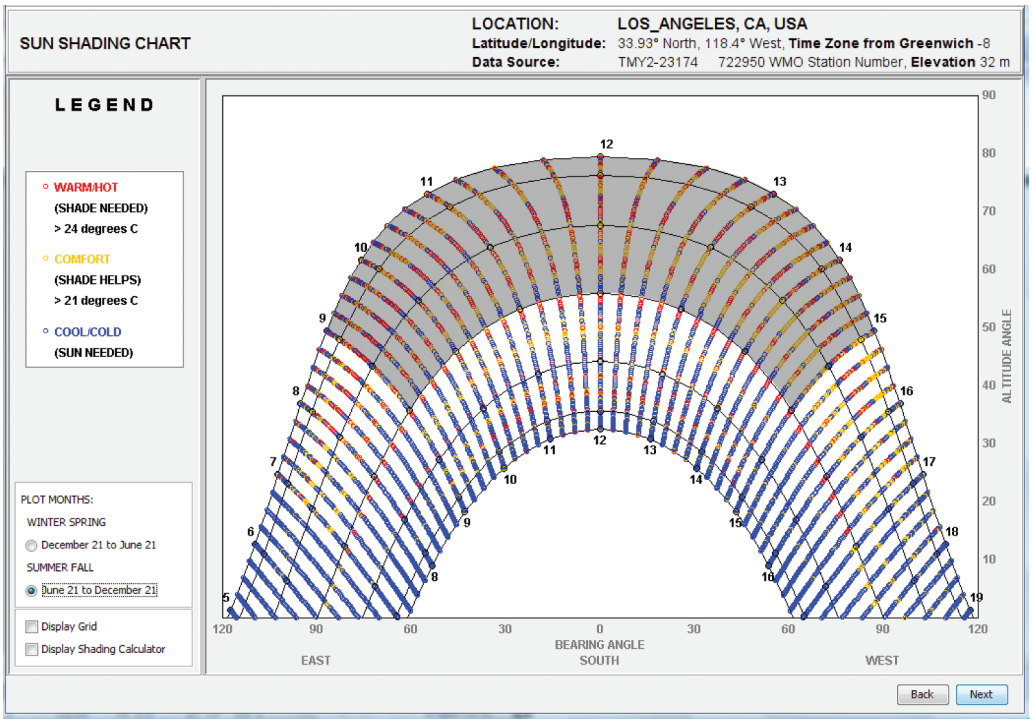


FIGURE 7.22 Vertical sun path diagram with temperatures for Los Angeles (June to December) indicating overheated areas which should be shaded.

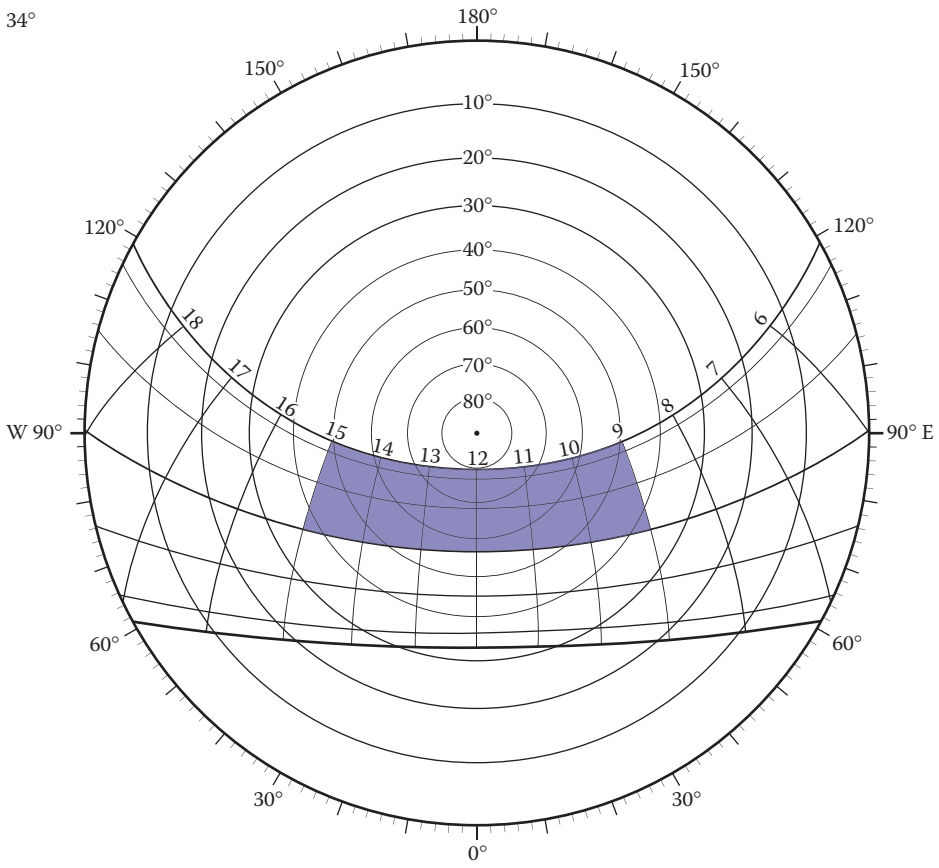


FIGURE 7.23 Horizontal sun path diagram with the same overheated area as Figure 7.21.

The period during which the windows must be protected from solar radiation is also indicated by the shaded area in a horizontal sun path diagram as determined by the analysis of climate data and solar geometry (Figure 7.23). Because it is a south-facing window, a line is drawn from east to west in the sun path diagram to represent this facade, and an arrow towards the south, perpendicular to this line indicates the orientation of the facade (Figure 7.24). Any point behind this line means that the sun is behind the facade and will not see the sun during those periods. This facade will not receive any sunlight before 8 a.m. or after 4 p.m. in June but receives sun during the whole day between September and March when the sun is lower in the sky. Only one orientation in one latitude can be studied at a time, each represented by different sun path diagram. However, the advantage is that the performance for the whole year can be visualized using only one image.

The next step is to place the solar protractor above the sun path diagram (Figures 7.25 and 7.26) with the bottom of the sun path diagram coincident with the facade line and the radius of the solar protractor matching the radius of the sun path diagram. The goal is to determine the angles (VSA or HSA) that best cover the shaded area. It is clear that a horizontal element is more effective to protect a south façade than a vertical element. If the VSA is too small, it will generate a component that will cover much more than is needed. If the angle is too large, the component will be too small. In this example, the angle that best covers the shaded area is about 62 degrees, equivalent to a VSA of 62 degrees. The VSA is drawn on the shadow protractor and then the shaded area of the protractor,

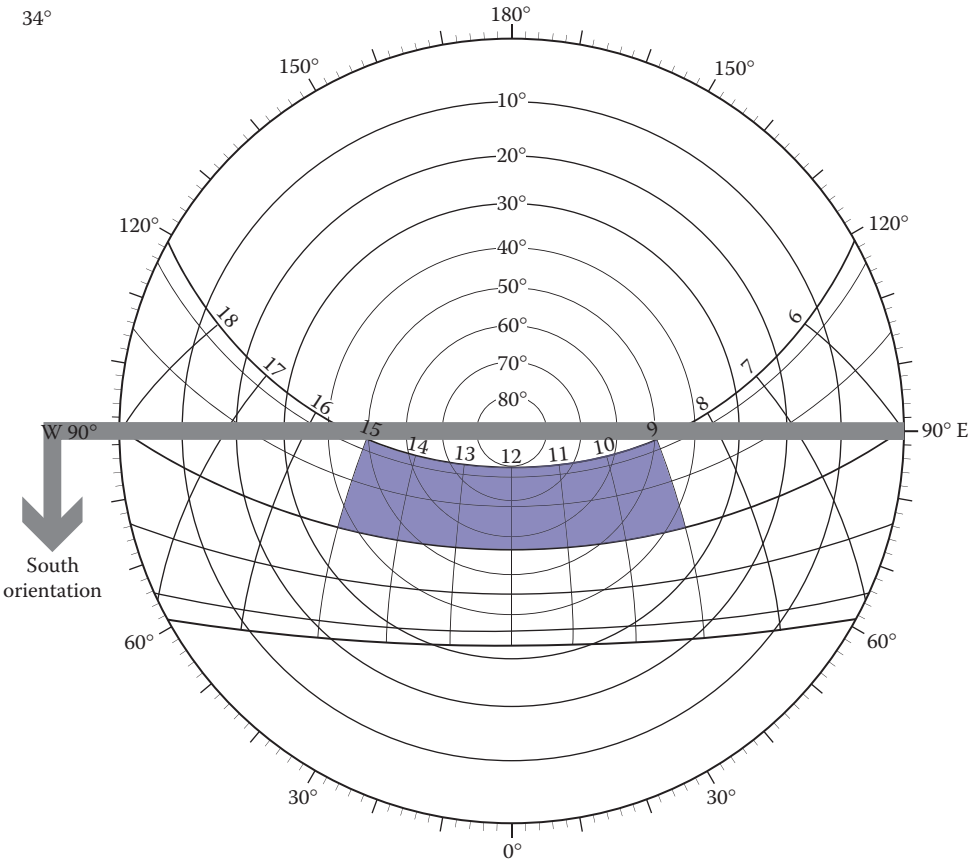


FIGURE 7.24 Overheated area in the sun path diagram with façade orientation.

called the shadow mask. The area shaded by a horizontal element sized to provide the required VSA protection is indicated in green (Figure 7.27).

To calculate the overhang (OP) needed to provide this VSA for a window height of 2 m, Equation 7.5 should be used:

$$\mathrm{OP} = \frac{\mathrm{HP}}{\tan \mathrm{VSA}}$$

$$\mathrm{OP} = \frac{2\ \mathrm{m}}{\tan 62^\circ}$$

$$\mathrm{OP} = \frac{2\ \mathrm{m}}{1.88}$$

$$\mathrm{OP} = 1.06\ \mathrm{m}$$

The advantage of defining the shading system with the VSA angle is that many different options can be generated from one angle: for example, two horizontal elements separated 1 m from each other and half the dimension of the original overhang (0.53 m); or sloped elements that

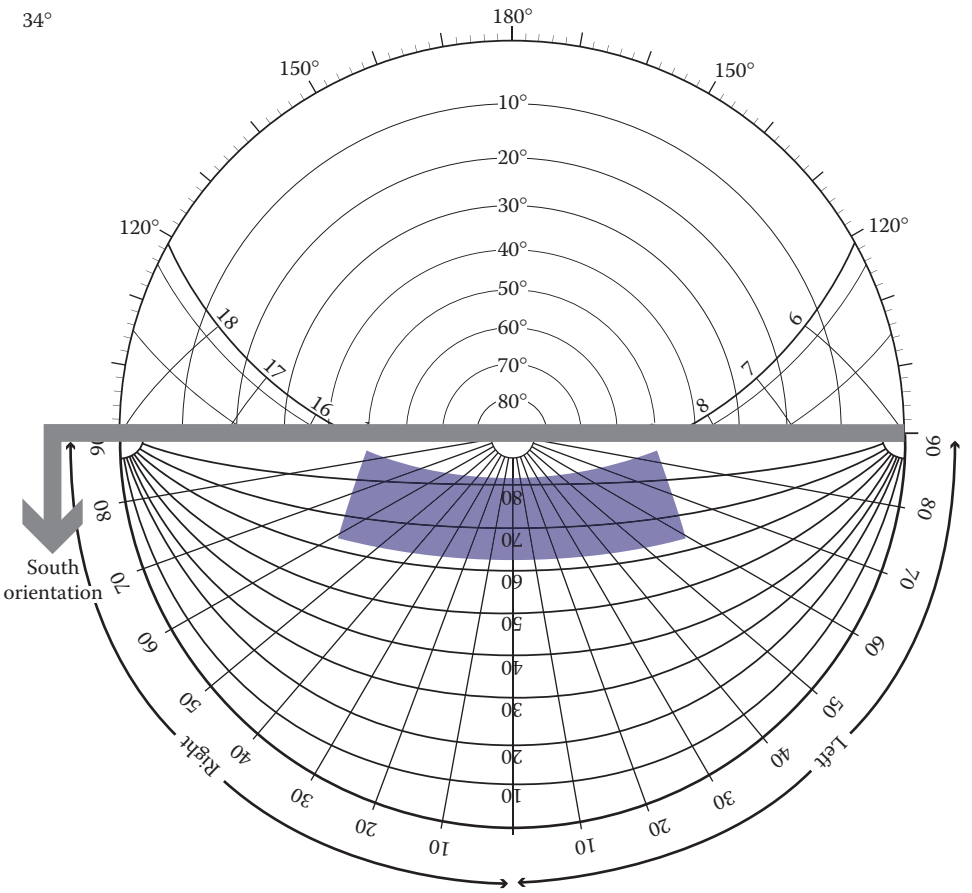


FIGURE 7.25 Sun path diagram with solar protractor.

provide the same angle. These can be progressively divided and subdivided until they are very small such as blinds, because the components can be defined as a function of the VSA. This shadow mask shows solar protection achieved by a horizontal element that extends beyond the window. A common error is to think that this level of solar protection can be reached with a horizontal element placed directly above the window and extending neither to the left nor the right of the window. If it did not extend beyond the window, then it would receive solar radiation from its sides.

It is immediately apparent from this example that for this latitude in an equatorial-facing facade, an overhang will easily provide the required solar protection—shade in the summer and free heating from the sun in the winter.

7.4.5 Example Design of a Shading for a Southeast-Facing Window

To shade the same window, which is now facing southeast, a similar process is followed. The facade and the shadow angle protractor are now both facing southeast (Figure 7.27). It is immediately apparent that the facade will not receive solar radiation during afternoon hours after around 1 p.m.

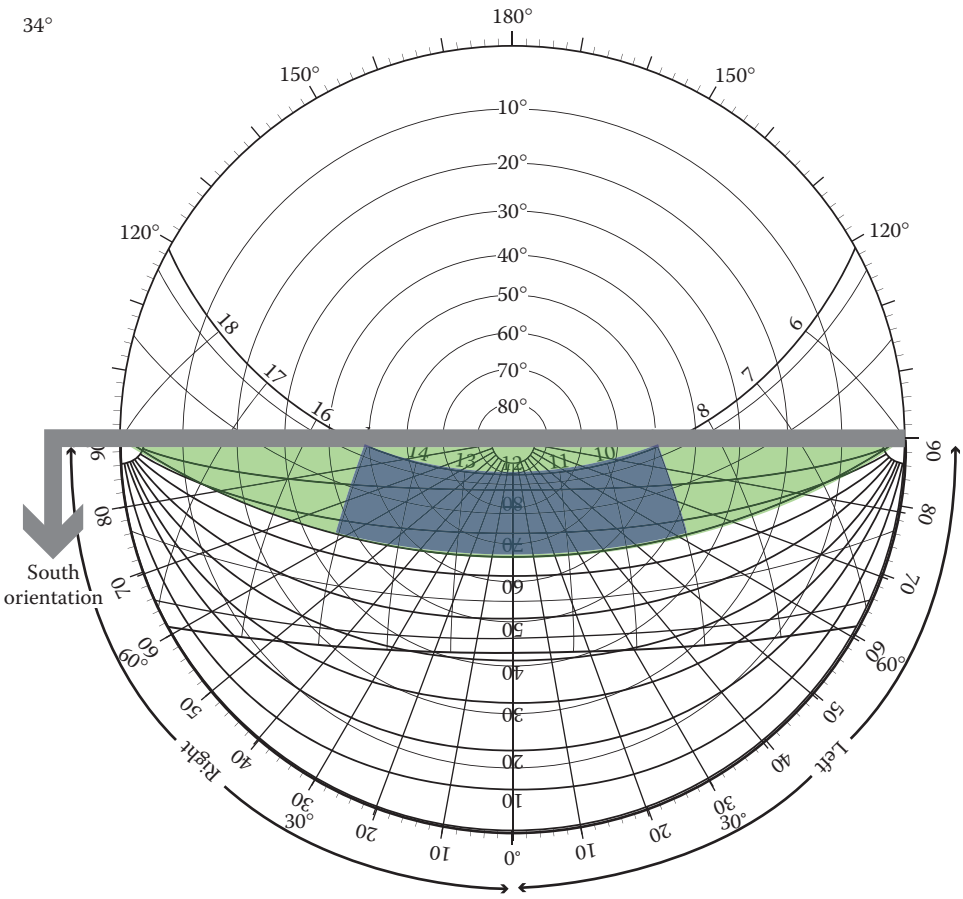


FIGURE 7.26 Solar protractor overlaid above the sun path diagram with a shadow mask.

(depending on the month). It is determined that a VSA of about 47 degrees provides the required shade. To calculate the dimension of the overhang, the same equation is applied indicating a recommended overhang of 1.86 m.

$$\mathrm{OP} = \frac{\mathrm{WH}}{\tan \mathrm{VSA}}$$

$$\mathrm{OP} = \frac{2\ \mathrm{m}}{\tan 47^\circ} = 1.86\ \mathrm{m}$$

The horizontal shadow angles are calculated using the radial lines from the center of the protractor and indicated on either side. A first test is done with the fin on the north side of the window and a HSA of 30°, which would be a significant fin, on the north side of the window (Figure 7.28) does not provide any shade at all. A fin with the same VSA on the south side of that window would provide

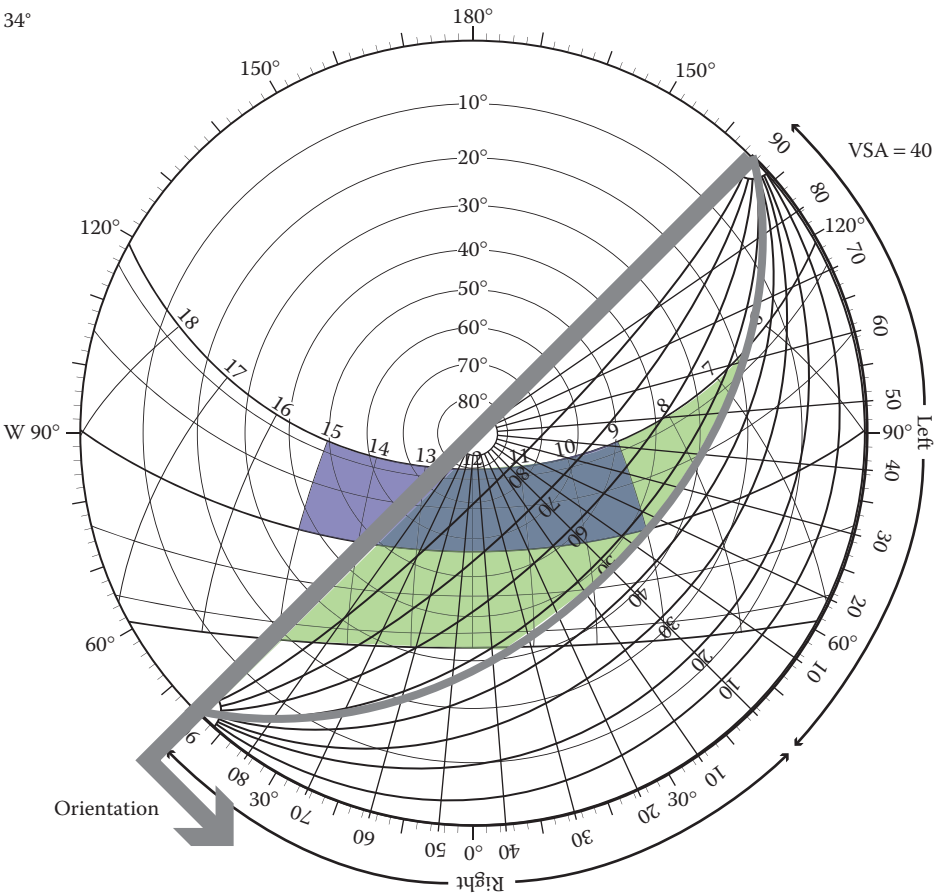


FIGURE 7.27 Southeast façade with the same conditions.

some shade from around noontime (Figure 7.29); however, this does not include solar radiation that enters when the sun is above the fin. A combination of horizontal and vertical components will properly shade this orientation.

$$\mathrm{FP} = \frac{\mathrm{WW}}{\tan \mathrm{HSA}}$$

$$\mathrm{FP} = \frac{2\ \mathrm{m}}{\tan 30^\circ} = 3.46\ \mathrm{m}$$

Sun path diagrams that also show temperature combined with solar protractors can be used to design horizontal and vertical shading elements for different orientations. However, buildings will have different levels of insulation and internal gains, which will affect thermal performance and the only way to determine if the performance of the shading system is to do an energy model that includes the shading system.

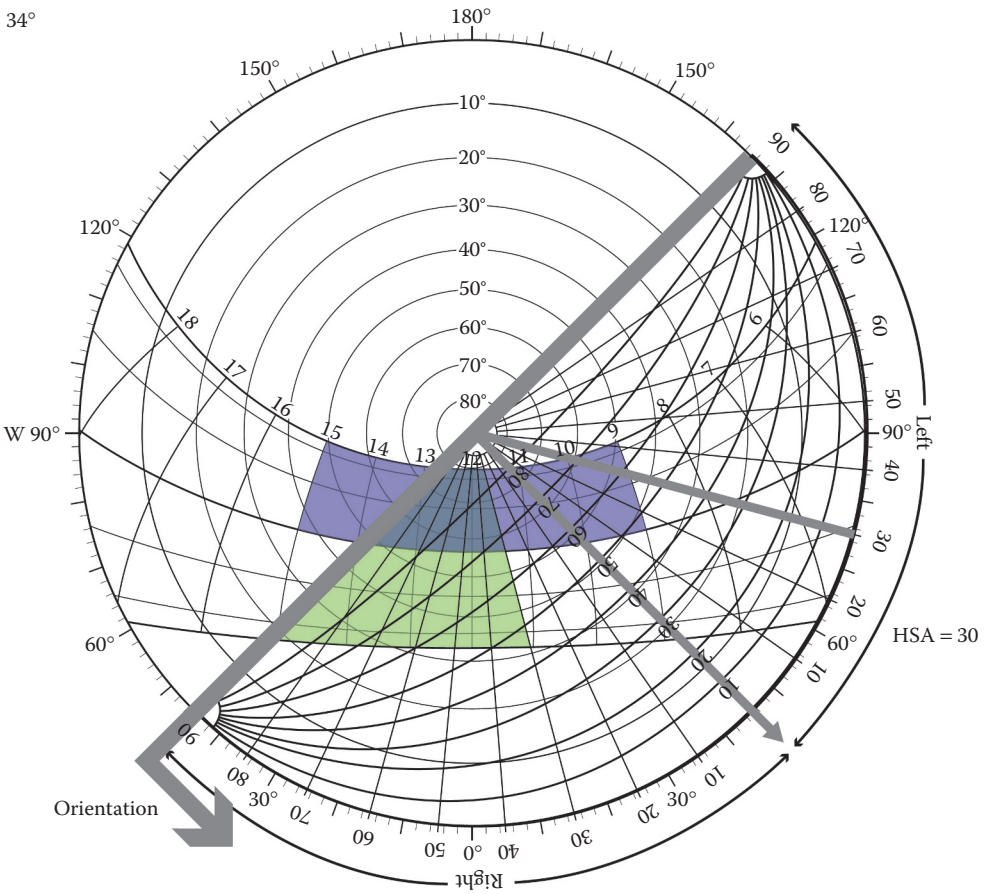


FIGURE 7.28 Solar protractor on the southeast façade.

7.5 SUNDIALS

A sundial can be used to analyze shading in a physical model. Sundials are also made for each latitude and require a gnomon of a particular height to cast the proper shadow. The length of the gnomon is indicated in each sundial so that enlargements or reductions can be made and the gnomon always stays in the correct proportion (Figure 7.30). To use the sundial, it must be pasted on a piece of cardboard in the same orientation as the model that is being tested to indicate the date and time for each shadow option as the model is rotated in different directions. Climate Consultant uses data from weather stations to provide temperature information to the sundial. The data in the chart is divided in three areas: cool, comfortable, and warm. The edges of these are based on the comfort zone model selected. For example, if the lower limit of the comfort zone is around 20°C, then the program recommends shade whenever outdoor temperature is above this temperature and absolutely whenever it is above the upper value of the comfort zone which in the image is 24°C. Thus, if the analysis is being done using the sundial in Figure 7.31, shading should be provided whenever the temperature is above 24°C, the lower limit of the selected comfort zone.

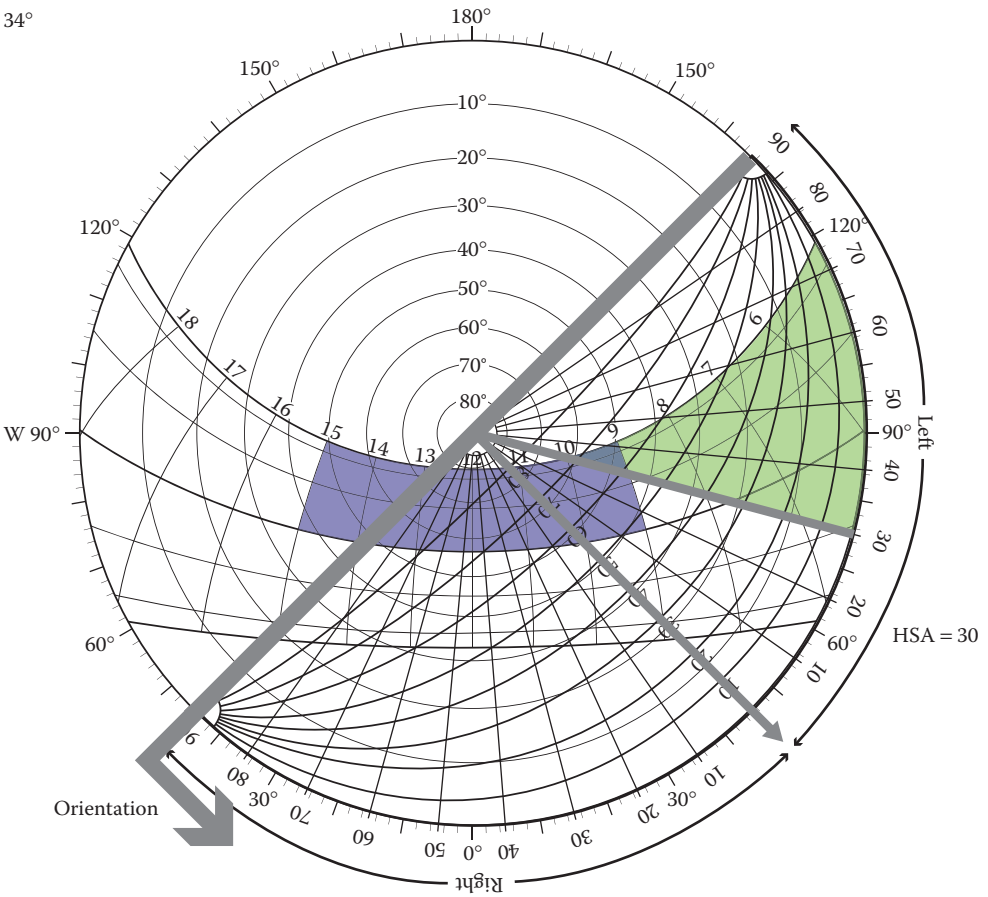


FIGURE 7.29 Shadow mask from a fin in the north side of the southeast window.

7.6 SITE ANALYSIS

Sun path diagrams can be used to determine solar potential of a location, especially to determine comfort, the placement of photovoltaic systems, or passive gains in a solar building. Building shading on outdoor spaces has an important effect on its perception and use. If it is intended for winter use and is shaded by a neighboring building, it will probably be dark, cold, and unused; and will not be used if it is unshaded and intended for use during hot weather. Sun path diagrams and shadow masks are used to determine shade from adjacent buildings, trees, or other obstacles. The position of the obstacles is calculated by determining the azimuths and altitudes of the edges of the points and plotting them on the sun path diagrams. The area that is intersected by the path of the sun and the enclosed surface indicates when the sun is blocked by obstacles. If the surface is outside the path of the sun, this means that the sun is not blocked by obstacles at any moment. Figures 7.32 and 7.33 show the same obstacles plotted on a vertical and a horizontal sun path diagram. A tree blocks the sun during a large part of the summer morning, and during the summer it is mostly clear close to noontime. Because the position of the obstacles on the sun path diagrams are the result of geometric relationships between the point in the site and the obstacles, the position of the obstacles on the chart

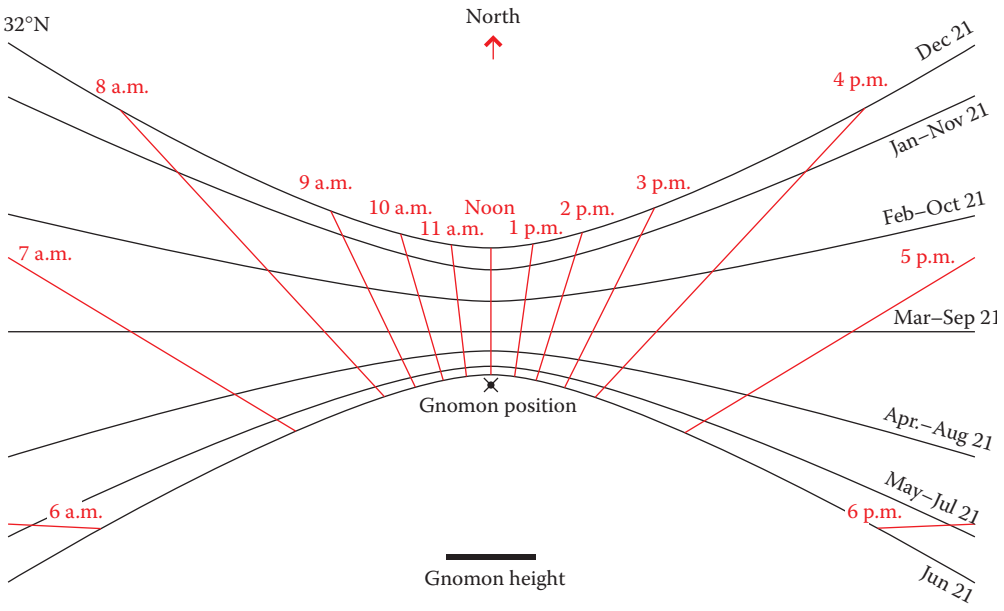


FIGURE 7.30 Sundial for 32° north latitude.

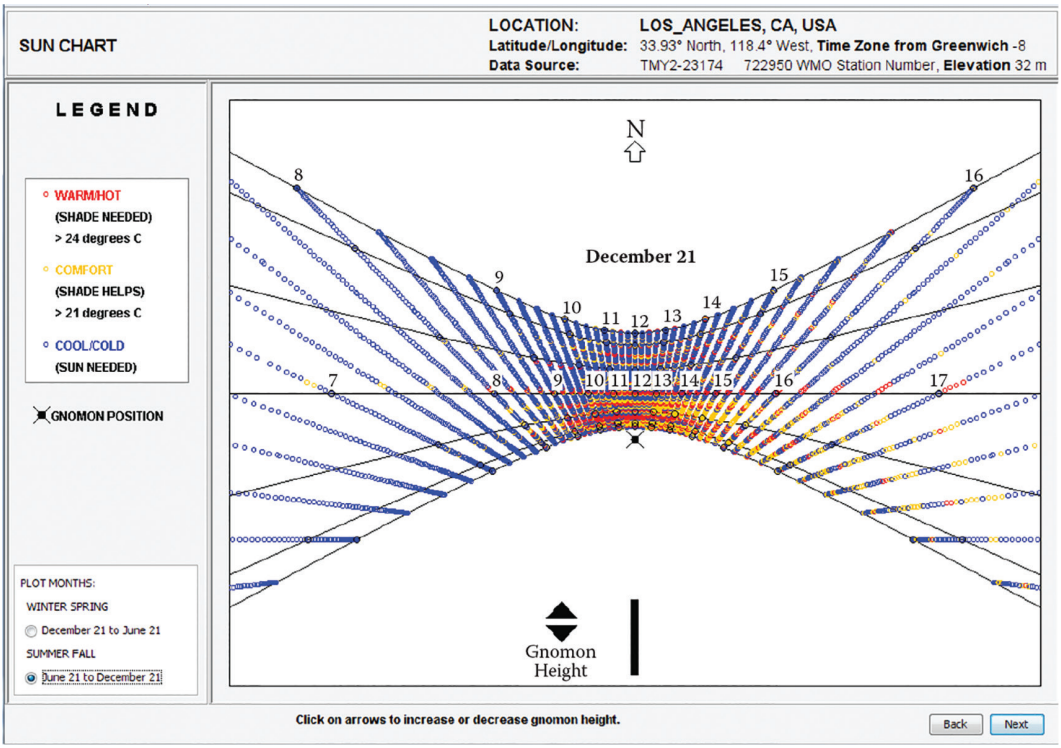


FIGURE 7.31 Sundial with temperatures for 32° north latitude using Climate Consultant.

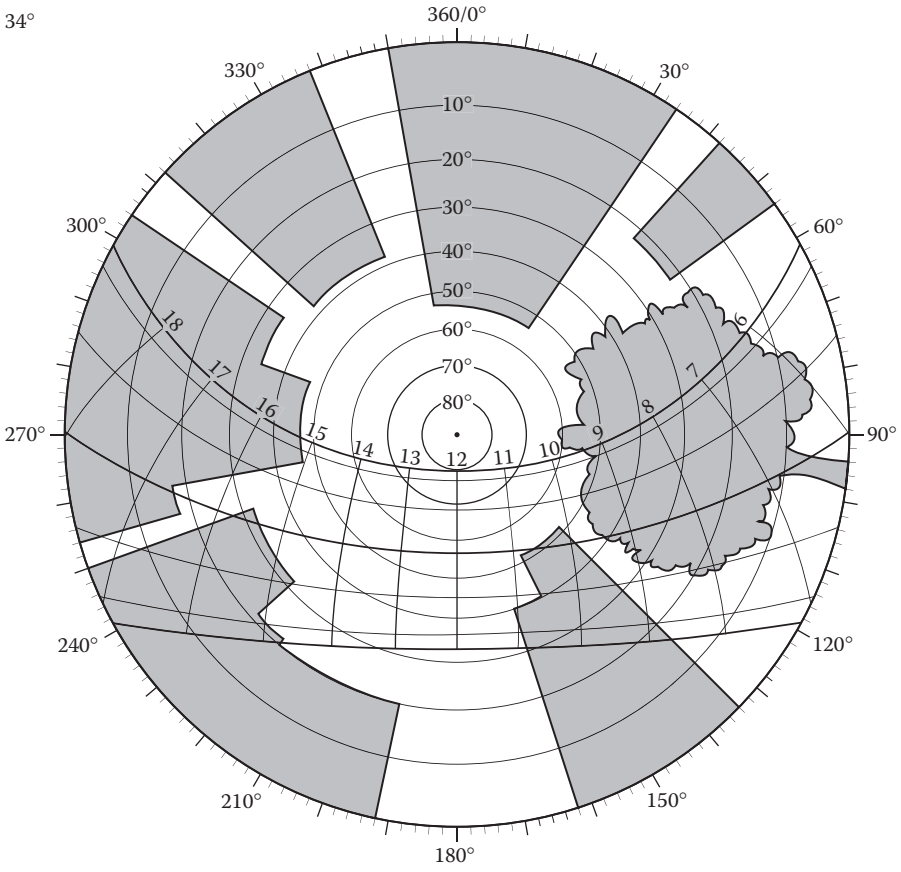


FIGURE 7.32 Site analysis on a horizontal sun path diagram.

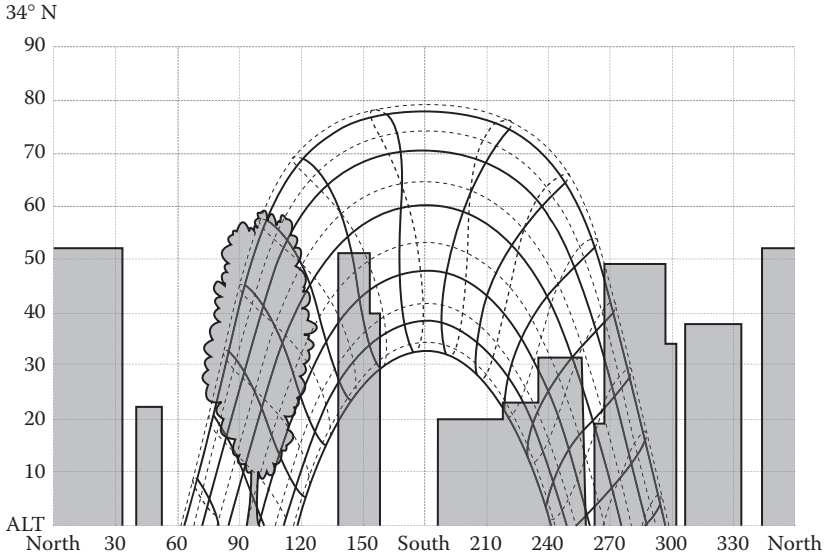


FIGURE 7.33 Site analysis on the vertical sun path diagram.

changes as we analyze different points. Because they indicate the times during which solar radiation will be available, these can also be used to establish performance of photovoltaic systems or direct gain systems for passive and active heating. Adjustments in building massing can then be proposed to improve shading or solar access. It is now also possible to generate these sun path diagrams with software.

In a manual analysis, the obstructions must be calculated and then drawn on the sun path diagrams. If the analysis is done digitally, then the obstructions are automatically calculated by the program, adjusting for the relationship between the sun and the obstacles.

7.7 FAÇADE ORIENTATION

The orientation of the building has a considerable effect on its thermal gains. A polar-facing orientation (north facing in the northern hemisphere and south facing in the southern hemisphere) receives direct solar radiation only in the early morning and late afternoon and close to the summer solstice and can be blocked with vertical elements such as fins.

Buildings that are further away from the equator receive more solar radiation in equatorial-facing facades as the building is located farther away from the equator. The angle of incidence also varies according to the latitude, being more perpendicular to the facade as the building is farther north. It is easy to adjust seasonal solar gains with horizontal elements in equatorial-facing façades in mid- to high latitudes.

In east-facing facades in the morning and west-facing facades in the afternoon, solar radiation hits the facade at low and difficult-to-protect angles, and to block the sun it is necessary to build large elements that block views and reduce daylight. Solar gains to the west are aggravated because of higher afternoon temperatures which increase heat gains by conduction.

In lower latitudes, close to the equator, the roofs receive the highest values of solar radiation as the sun rises quickly in the sky. In all latitudes, the roof gains more heat in the summer and less in the winter. This is in direct contrast to an equatorial-facing façade in a mid latitude climate, which tends to gain more heat in the winter than in the summer.

7.8 USING SHADOW ANGLES AS A DESIGN TOOL

Solar radiation entering through windows can contribute a significant amount of heat into the building, which can be beneficial when heating is required but is also a liability when cooling is needed. Solar radiation can be controlled with properly designed shading systems that also provide daylight during the whole year. All glass buildings can look very beautiful in renderings; however, they can lead to overheating and glare on the inside, forcing the occupant to close their blinds to try to avoid direct sun. Unfortunately after the blinds are closed, they usually stay closed, blocking the view and reducing daylight (Figure 7.34).

While at HMC Architects, the author led the sustainability team involved in the Design of a Classroom building at Cal State University Monterey Bay. A key design feature was the shading system for the large southwest facade. Because of cost and maintenance issues (close to the ocean), it was not possible to propose operable exterior shading. However, the responsiveness in the facade was achieved by designing the fixed elements to optimize the performance of each space as a function of its orientation and program, creating a visually complex and interesting façade.

The climate in Monterey is very mild, with the highest temperatures in March, April, August, September, and October. This is also when the skies are clearest, combining high solar radiation, and temperatures, especially in the afternoon, which can overheat the building (Figures 7.35 and 7.36). The south and west façades should block solar radiation in critical afternoon hours, from April to September between 12 and 4 p.m.

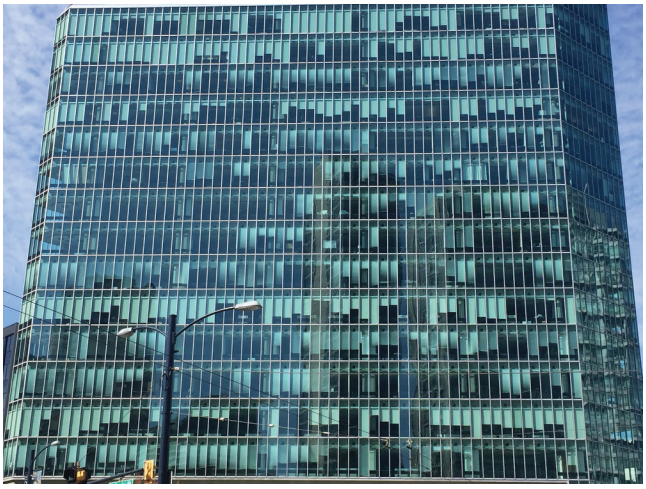


FIGURE 7.34 Unshaded building with multiple interior blinds closed.

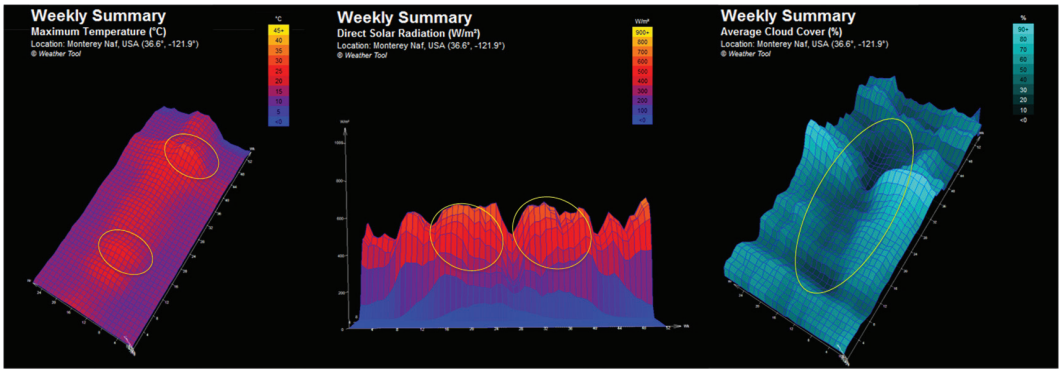


FIGURE 7.35 Cloud cover and temperature in Monterey Bay.

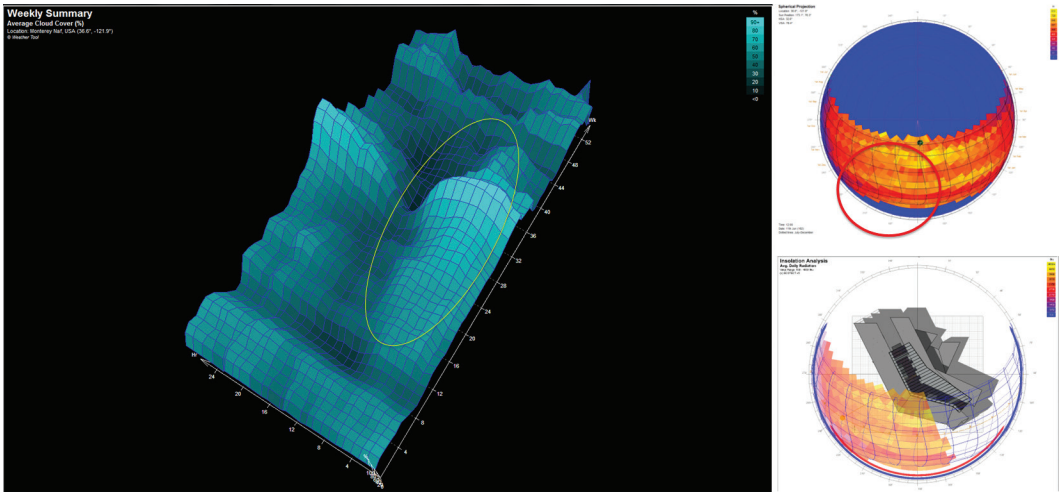


FIGURE 7.36 Solar radiation and cloud cover in Monterey Bay. (Courtesy of HMC Architects.)

The shading goals were to (a) provide shade in the critical summer months, especially August and September afternoons, blocking direct heat to the interior of the space; (b) control glare all year, in varying levels depending on the program. For example, glare was more critical in a lab space, and was deemed more acceptable in the office space in favor of view; (c) provide potential for passive heating in the winter; (d) provide daylight to satisfy LEED requirements (10–500 fc at Sept 21 at 9 a.m. and 3 p.m.); and (e) satisfy additional specific daylighting requirements.

We looked at the program on the west façade and drew it in the façade proposing different levels of wall porosity, varying according to the orientation and the program. The spaces were divided in seven categories: labs, lecture halls, office spaces (including conference rooms and meeting areas), workrooms, lounges, circulation, and storage (Figure 7.37). Each space type was assigned a design value for daylighting, which in turn defined the necessary porosity for the shading system to achieve required indoor conditions. These porosity levels were organized in tables for the different orientations and adjustments were made to provide views for additional solar protection in critical areas of the building or opportunities for passive solar gain.

The façade was initially divided in three orientations, 15, 58, and 68 degrees from south and later simplified to just two orientations: 24 and 63 degrees from south. The 15 degree orientation was the closest to south and a VSA of about 55 degrees was sufficient to provide enough shade until mid-September. For the orientations at 58 and 68 degrees, a horizontal shadow angle of about 15 degrees on the west side would work. Table 7.1 describes conditions and guidance on the porosity level for each program, and was meant as a guide, not to be followed exactly.

Figure 7.38 shows a façade section, also divided in porosity levels, now responding to shade and view requirements. The porosity level in the façade is a function of the values indicated in Table 7.1.

For durability, a ceramic baguette system was proposed, which consisted of two basic elements: a Square Tubular Baguette 60 mm × 60 mm (2.36 in × 2.36 in) and a rectangular tubular louver 60 mm × 120 mm (2.36 in × 4.72 in), thus the module for the façade elements is 60 mm (or 2.36 in). The rectangular baguette can be mounted both vertically and horizontally, increasing the visual complexity without the need for additional elements. When it is in horizontal position, it also works better toward the south side. Figure 7.39 shows layout options for the baguettes as a function of the shade requirements for the low porosity and high porosity areas. With just two baguette sizes, it was possible to develop different combinations that achieve the same level of performance, maintaining an interesting and varied visual effect without compromising performance. These baguettes are combined to generate options that can achieve the same level of shading, even if they are different, generating infinite number of combinations with similar performance. Even if the final result looks complex, unity of composition is maintained over the total length of 316 feet of West-Southwest façade, while also responding to the program requirements. At the end, a small number of components was built in Revit and combined in the façade.

To study the density and design of the baguettes in the facade in more detail, a model was three-dimensional printed (Figure 7.40). Studies were done also to produce natural ventilation and daylight in the office spaces (Figures 7.41 and 7.42).

Many shading options were studied, some were vertical, some horizontal, and some a combination of vertical and horizontal (Figure 7.43). The final option was designed all with horizontal baguettes, in a limited number of panels and distributed and organized in the façade according to the established rules (Figures 7.44 through 7.48).

The same design strategy was implemented in another façade system in Santiago, Chile. Figure 7.49 shows the program in the façade and Figure 7.50 shows two responses to the program, with similar densities in key areas.

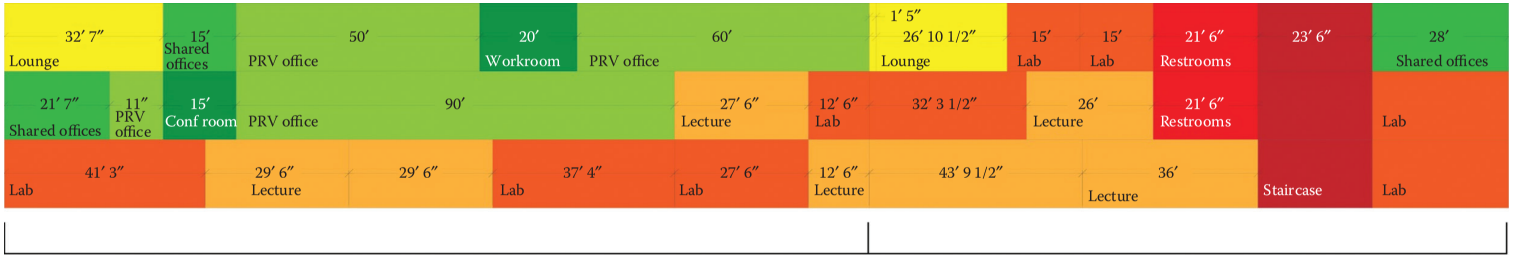


FIGURE 7.37 Layout of the program in the façade. (Courtesy of HMC Architects.)

TABLE 7.1
Program Requirements and Orientation

Program	63 degrees In General More of the Baguettes Tighter Together Over All of the Façade and More Toward the Top So that They Block the Glazed Portion	24 degrees In General More of the Louvers Are Horizontal and More Evenly Distributed in the Façade, This Façade Is More
Lab Should have views, no glare, 5–20 fc	70% closed	More of the louvers are horizontal and about 30% closed
Lecture Limited view, no glare	Baguettes toward the top 60% closed	More of the louvers are horizontal and about 20% closed
Offices Should have views, no glare, 5–20 fc	Baguettes toward the top 50% closed	Baguettes toward the top with passive heating wall at bottom.
Circulation glare is OK	Wide apart separation	Wide apart separation
Workroom glare is OK	No shade	No shade
Lounge Most views, glare is OK	Few baguettes and 20%–30% shade	No shade. Just a couple for rhythm 10% shade
Storage No views, glare is OK	Very few baguettes. Just a couple for rhythm 10% shade	No shade

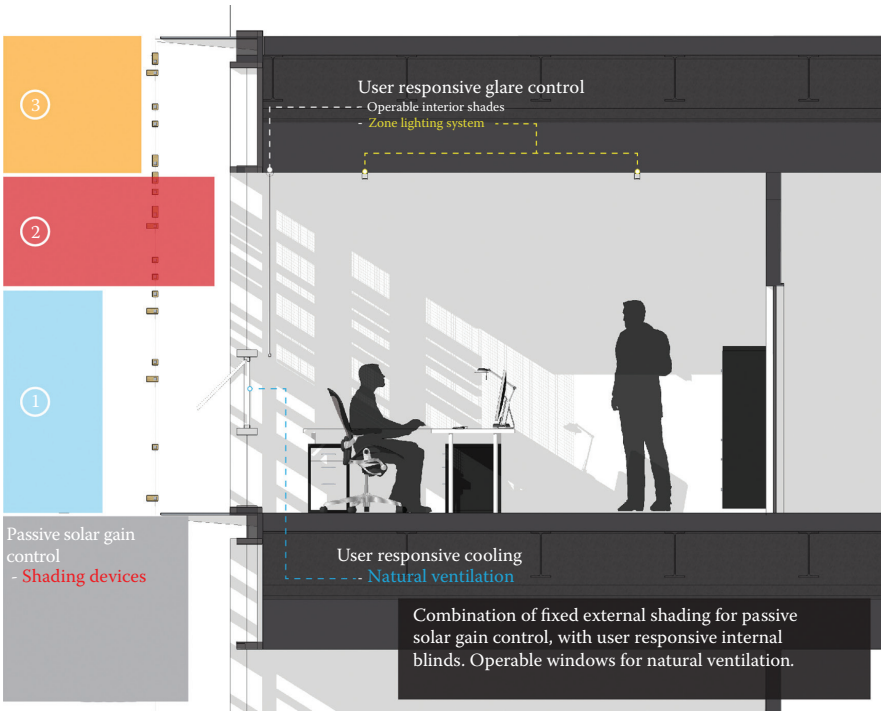
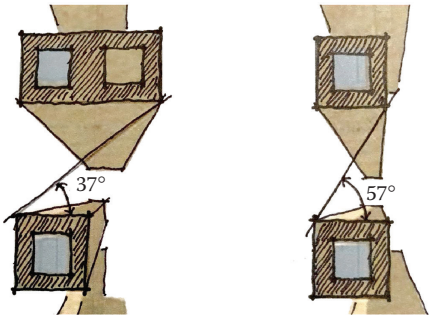
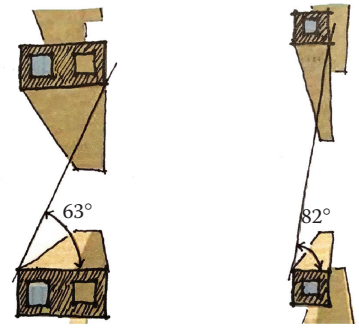


FIGURE 7.38 Porosity level in section. (Courtesy of HMC Architects.)



Low porosity/high density
VSA = 37°–57°
Spacing = 6″ OC



High porosity/low density
VSA = 63°–82°
Spacing = 12–18″ OC

FIGURE 7.39 Ceramic baguette combinations used in the different porosity levels.

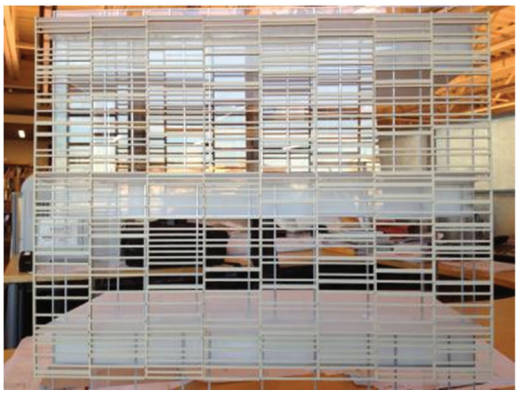


FIGURE 7.40 Photographs of 3D print model of the façade.

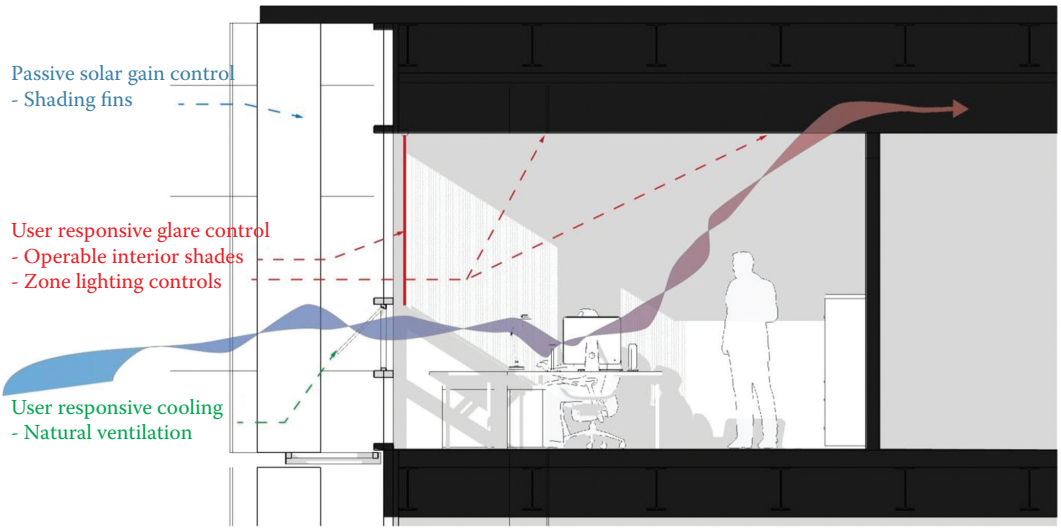
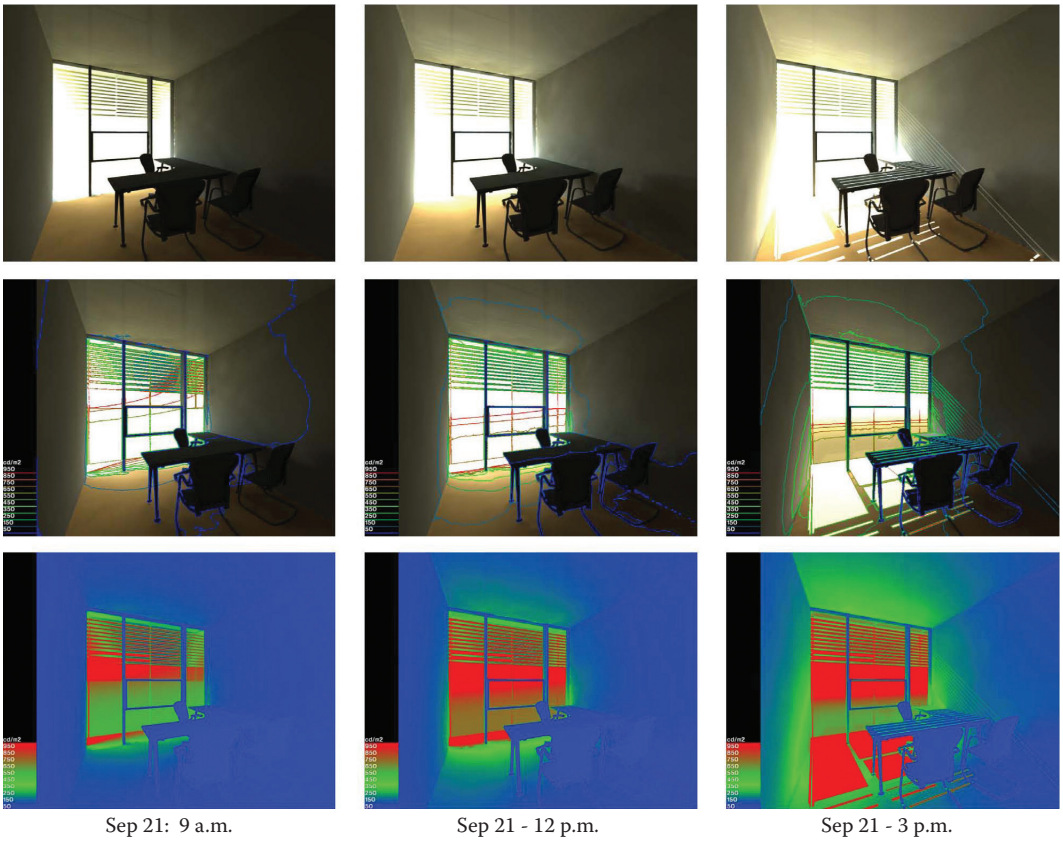


FIGURE 7.41 Performance section. (Courtesy of HMC Architects.)



Sep 21: 9 a.m. Sep 21 - 12 p.m. Sep 21 - 3 p.m.

FIGURE 7.42 Daylight analysis. (Courtesy of HMC Architects.)

FIGURE 7.43 Rendered image of a facade version. (Courtesy of HMC Architects.)

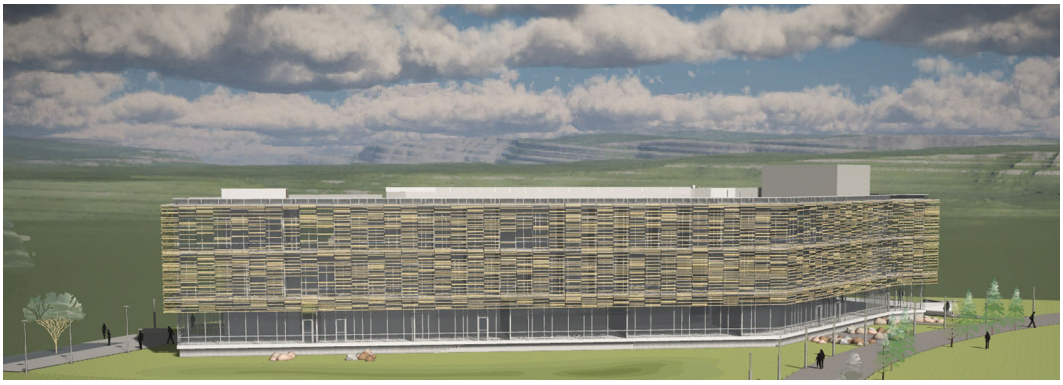


FIGURE 7.44 Rendered image of a façade version. (Courtesy of HMC Architects.)

FIGURE 7.45 Photograph of façade under construction with baguette shading.

FIGURE 7.46 Photograph of façade with baguette shading.

FIGURE 7.47 Photograph of façade with baguette shading.

FIGURE 7.48 Photograph of façade with baguette shading.

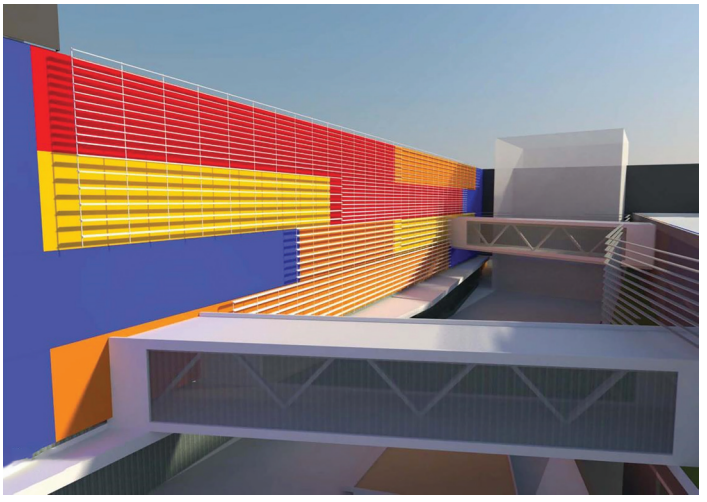


FIGURE 7.49 Program analysis to determine shading, daylighting, and view requirements.

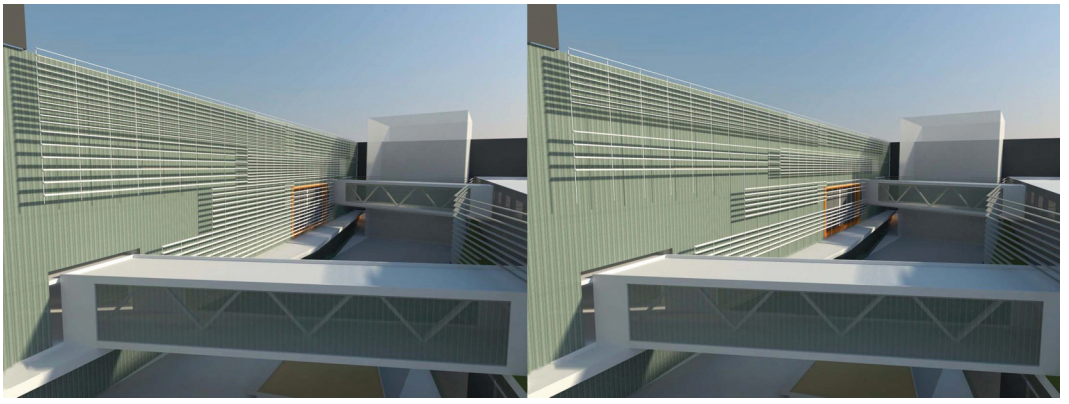


FIGURE 7.50 Shading options as a function of program analysis.

7.9 CALCULATING THE IMPACT OF RADIATION ON SURFACES

Building surfaces receive varying amounts of solar radiation depending on the climate and latitude of the site and the orientation and tilt of the surface. Incident solar radiation can significantly impact buildings by affecting the surface temperature of opaque materials, increasing the rate of heat transfer by conduction through walls, or by radiation and conduction through windows. Surfaces that receive more solar radiation might require additional shading during the summer, would be suitable for solar hot water collectors or photovoltaic panels, to place a window to provide solar gains to the interior of the building. The analysis period is determined by the design objective.

Using the methods previously described, it is possible to calculate shading systems to protect building components (e.g., a window). These calculations describe when the building component is receiving direct solar radiation (shaded or unshaded). However, this does not include the effects of diffuse and reflected solar radiation. In a warm and humid climate, a large part of the solar radiation incident on the building will be diffuse, and light-colored surfaces around the building could provide large amounts of reflected radiation affecting the design even more. It is now possible to analyze building components and complex forms with more precision using energy modeling tools.

With software such as IES and DIVA, incident solar radiation on a surface can be calculated and compared, allowing designers to make more informed design decisions regarding building geometry or the effects of shading on a façade. These programs typically allow the selection of analysis periods, which can be the same as the periods for which shade was calculated. Figure 7.51 shows as an example, incident solar radiation (diffuse, direct, and total) in a project in a warm climate in China. Incidence of solar radiation can help define shading requirements; for example, less shading can be proposed in surfaces with less solar radiation.

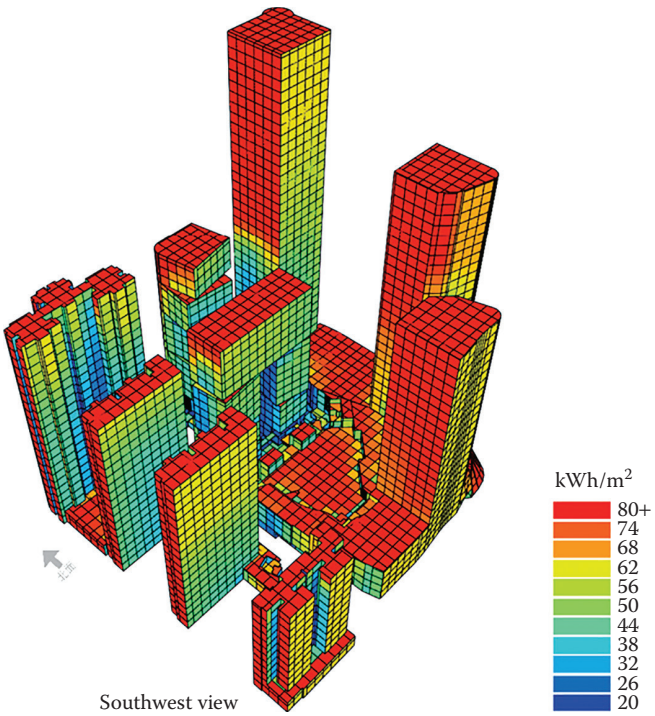


FIGURE 7.51 July accumulated diffuse and direct solar radiation in a mixed use project in China. (Courtesy of CallisonRTKL.)

8 Heat Exchange through the Building Envelope*

8.1 HEAT TRANSFER THROUGH THE BUILDING ENVELOPE

The design of the enclosure has an important effect on the performance of the building: The envelope affects the thermal interaction with the outdoors, the availability of daylighting, the psychological connection with the outdoors, and many aspects of occupant comfort. This chapter deals with the control of the flow of energy between the interior and the exterior of the building, through the enclosure, to achieve thermal comfort.

Energy is the ability to or capacity for doing work, and heat is a form of energy that appears as molecular motion in substances or as electromagnetic radiation in space. The most common units for heat are the British thermal unit (Btu) and the joule (J). One Btu is the amount of heat required to raise the temperature of 1 pound of water through 1°F (58.5°F–59.5°F) at sea level (30 inches of mercury). The standard unit of energy in the International System of Units (SI) is the joule, equal to the work done when a force of 1 Newton acts through a distance of 1 meter; 1 J is 1 watt-second. The kilowatt-hour (kWh) is used to measure electrical energy and is equal to the work done by 1 kilowatt acting for one hour; 1 kWh of electricity is 3.6 megajoules, or 3,412 Btu.

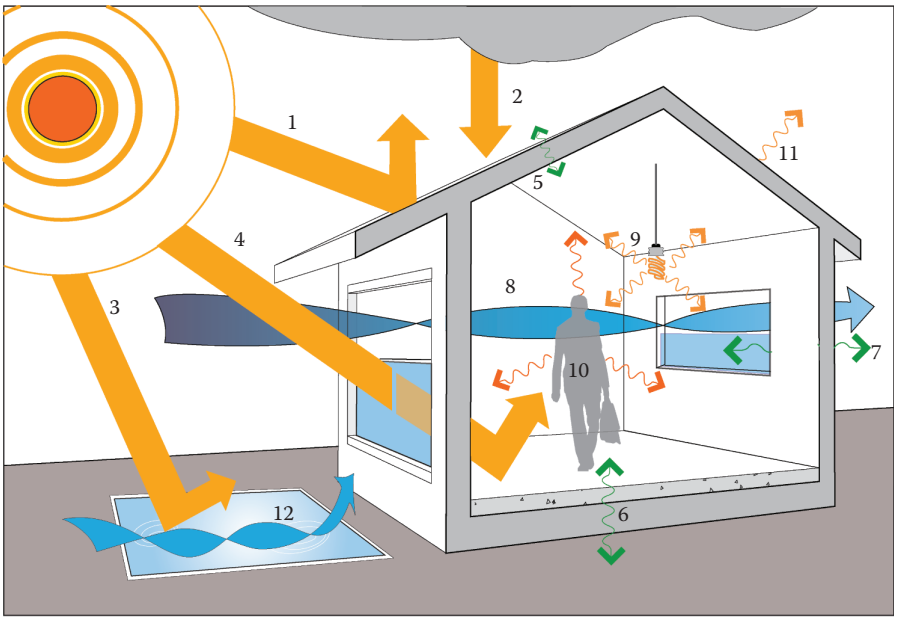
Temperature is a physical property that quantitatively expresses the presence of heat in a substance; the same material (same density and specific heat) with a higher heat content has a higher temperature. The basic unit of temperature in the SI units is the kelvin (K). However, for everyday applications, the Celsius scale is usually used, in which 0°C corresponds to the freezing point of water and 100°C is its boiling point at sea level. In the Inch Pound (IP) system, the Fahrenheit scale is used, in which water freezes at 32°F and boils at 212°F.

A building will always try to attain thermal equilibrium with the outdoors, and heat can flow toward the interior or the exterior but always from a higher to a lower temperature. Heat transfer through the enclosure can be by conduction, radiation, or convection. These flows can occur through the different components of the building fabric: Conduction occurs through the solid components of the building, radiation occurs through materials that have transparency and also affects opaque materials, and convection occurs through any opening or crack in the building. Mechanical systems also move heat between the inside and outside of the building but are not discussed in this book.

Understanding these flows helps the designer to identify building design strategies that could be implemented to prevent building overheating or overcooling and to improve the overall thermal quality and energy efficiency of the building. Optimum control of these flows will reduce the energy required for heating and cooling and associated greenhouse gas (GHG) emissions. The ultimate goal is to achieve thermal comfort with strategies that control energy flows through the building fabric without the need for mechanical systems. Implementing these strategies in the building fabric is a necessary first step to improve performance of all systems: passive, active, mechanical heating and cooling, and renewable.

This chapter deals with how to use the building fabric to control flows to reduce summer overheating and winter overcooling. When buildings overheat or overcool, the traditional solution is to pump heat inside or outside; however, these flows can be reduced with appropriate design of the envelope so that it is cooled and heated naturally, using just the envelope.

* Much of this chapter was first developed in La Roche, P., Quirós, C., Bravo, G., Machado, M., and Gonzalez, G. (2001). Keeping Cool Principles to Avoid Overheating in Buildings, Plea Note 6, Passive Low Energy Architecture Assoc. and Research Consulting and Communications.



1. Beam (direct) solar radiation (Gb)
2. Diffuse solar radiation (Gd)
3. Ground-reflected solar radiation (Gr)
4. Window solar radiation
5. Envelope heat conduction
6. Ground heat conduction
7. Window heat conduction
8. Ventilation heat transfer
9. Electric lights and appliances
10. Occupants heat contribution
11. Sky longwave radiation
12. Evaporative cooling

FIGURE 8.1 Thermal exchanges between a building and the environment.

The different thermal phenomena that must be considered when designing for the control of energy flows are beam or direct solar radiation, diffuse solar radiation, ground-reflected solar radiation, window solar radiation, envelope heat conduction, ground heat conduction, window heat conduction, ventilation heat transfer, electric lights and appliances, heat contribution from occupants, sky longwave radiation, and evaporative cooling (Figure 8.1).

The radiant energy flow from the sun can arrive at ground level in two forms, beam or direct (Gb) and diffuse (Gd), both of which are indicated in Figure 8.1 as (1) and (2). The surfaces around the building also reflect solar radiation (Gr), which can be significant when the albedo of these surfaces is high. Solar radiation can affect heat flow by conduction through opaque surfaces (5) and transparent surfaces (Q_{sw}) (4). The effect of solar radiation on opaque surfaces is included in the heat flow by conduction, and Q_c is the sum of the heat flows by conduction through the solid components of the envelope (opaque or transparent) and includes envelope heat conduction (5), ground heat conduction (6), and window heat conduction (7) in Figure 8.1. Q_{cv} is the result of air mass exchange and is ventilation heat transfer (8) in Figure 8.1. Heat flow (Q_{ir}) is radiant longwave (infrared) cooling, and Q_{ev} is evaporative cooling (11 and 12 in Figure 8.1) and is discussed in the section on passive cooling in Chapter 9.

The heat balance equation, in a simplified form, based on the superposition of steady and periodic thermal phenomenon is used to determine when it is helpful to block or promote thermal flows as shown in Figure 8.1. This equation is adapted from Lavigne, Brejon, and Fernandez (1994) and was used by La Roche, Quirós, Bravo, Machado, and Gonzalez (2001) to organize the strategies that can reduce overheating in buildings.

$$Q_{sw} + Q_i \pm Q_c \pm Q_{cv} - Q_{ir} - Q_{ev} = 0 \tag{8.1}$$

where:

Q_{sw} is the solar heat flow transferred through windows (solar gain)
Q_i is the heat generated inside the building (internal gain)
Q_c is the conduction heat flow through envelope components (includes effect of solar radiation)
Q_{cv} is the heat flow by ventilation and infiltration
Q_{ir} is the net long wave radiation heat flow
Q_{ev} is the heat loss by evaporation

In this equation, all heat flows may be instantaneous, but to simplify analysis they are often considered as average values for a period, usually 24 hours. In this case, heat gains and losses represent the daily heating and cooling of the building. Conduction heat flow through the envelope (Q_c) is the sum of the transmittance (U-value) and area (A) of all envelope elements, often referred to as the envelope conductance of the building (Q_c = sum [UA] in units of W/K) and the difference between outdoor and indoor temperatures ($T_o - T_i$). Heat transfer due to air mass exchange (Q_{cv}) is the result of natural or mechanical ventilation or air infiltration: $v_r \times c \times (T_o - T_i)$, which is the product of airflow (v_r = ventilation rate in m^3/s) multiplied by the volumetric specific heat of air (J/m^{3}K) often denoted as q_v, or ventilation conductance, and the temperature difference, as presented already. If $T_i > T_o$, then $T_o - T_i$ gives a negative result (i.e., heat loss), whereas if $T_i < T_o$, then the result is a heat gain. Figure 8.2 illustrates the variables that affect the heat balance in a building.

As a result of solar exposure and indoor heat generation, the interior average temperature of a building without mechanical or passive cooling in the summer will always be higher than the outdoor temperature and probably above the comfort zone. Also, because of thermal gains, the indoor average temperature in an unconditioned building in the winter will be higher than the outdoor average temperature; however, depending on the magnitude of the outdoor temperature, it will probably be below the comfort zone. To achieve indoor temperature values closer to the comfort zone, overheating should be reduced in the cooling season, and overcooling should be reduced in the heating season. This is achieved by keeping the heat out in the summer and keeping it inside in the winter.

To better illustrate this process, Tables 8.1 and 8.2, which are both loosely based on Watson's and Labs (1983), as well as diagrams including the components of Equation 8.1 are provided in this chapter to illustrate the strategies that can be used to block, control, or promote heat flows and to avoid overheating or underheating of the building. These same principles are also explained graphically in Figures 8.3 and 8.4. Each heat flow, as well as criteria or design principles that should be applied to reduce its magnitude, is discussed in the following sections.

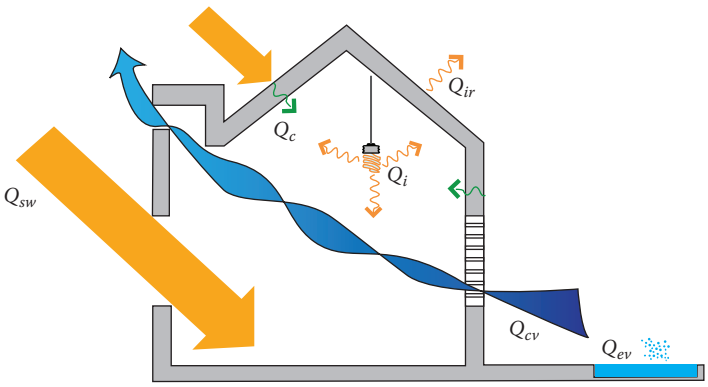


FIGURE 8.2 Variables that affect the heat balance in a building.

TABLE 8.1
Strategies to Prevent Overheating

Strategies and Heat Flows	Heat Flows to Be Blocked	Heat Flows to Be Controlled	Heat Flows to Be Promoted
Q_{sw}			
Q_i			
Q_c			
Q_{cv}			
Q_{ir}			
Q_{ev}			

Source: Based on D. Watson and K. Labs, *Climatic Design, Energy Efficient Building Principles and Practices*, McGraw-Hill, New York, 1983.

TABLE 8.2
Strategies to Prevent Overcooling

Strategies and Heat Flows	Heat Flows to Be Promoted	Heat Flows to Be Controlled	Heat Flows to Be Blocked
Q_{sw}			
Q_i			
Q_c			
Q_{cv}			
Q_{ir}			
Q_{ev}			

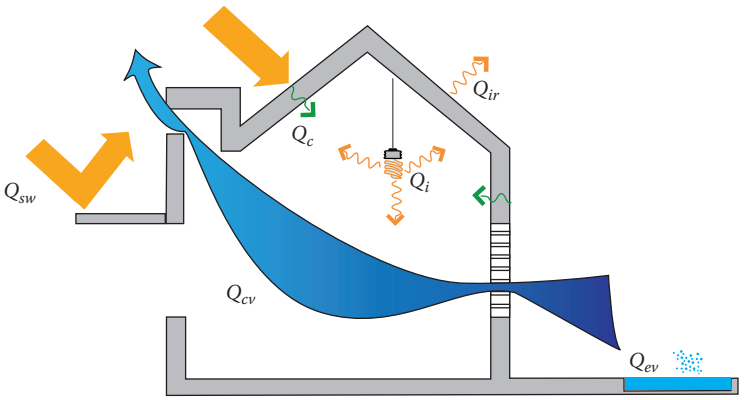


FIGURE 8.3 Strategies to prevent overheating in the summer.

Considering temperatures and mass and heat flows as average values of a 24-hour period, the average temperature difference between the interior and the exterior of a building (ΔT_m) can be expressed by modifying Equations 8.1 and 8.2. In this equation, the numerator includes the flows, and the denominator includes the building components that regulate them:

$$\Delta T_m = T_{om} - T_{im} = \frac{Q_{swm} + Q_{im} - Q_{irm} - Q_{evm}}{q_c + q_v} \tag{8.2}$$

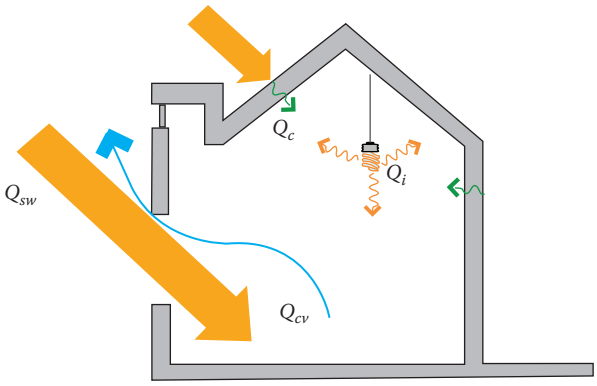


FIGURE 8.4 Strategies to prevent overcooling in the winter.

$$T_{im} = T_{om} + \Delta T_m \tag{8.3}$$

where:

q_c is the sum ($A \times U$) = envelope conductance (W/K)
A is the surface area of each envelope component (m^2)
U is the transmittance of each element (W/m^2K)
$q_v = v_r \times c$ is the ventilation conductance (W/K)
v_r is the ventilation rate (m^3/s)
c is the volumetric specific heat of air (usually 1,200 J/m^3K)
T_{im} is the mean indoor air temperature (°C)
T_{om} is the mean outdoor air temperature (°C)
$q = q_c + q_v$ is the building conductance (W/K)

Indoor building temperature varies around T_{im} with a $\Delta T_{im}/2$ value, where $\Delta T_{im} = T_{i(\max)} - T_{i(\min)}$; then the interior temperature (T_i) in any given moment can be expressed as

$$T_i = T_{em} + \frac{Q_{svm} + Q_{som} + Q_{im} - Q_{irm} - Q_{evm}}{q_c + q_v} \pm \tfrac{1}{2} sT_i \tag{8.4}$$

where sT_i is the swing of indoor temperature from the mean, T_{im}.

Accordingly, maximum and minimum temperatures can be expressed as

$$T_{i(\max)} = T_{om} + \Delta T_m + \frac{1}{2}\Delta T_{im} \tag{8.5}$$

$$T_{i(\min)} = T_{om} + \Delta T_m - \frac{1}{2}\Delta T_{im} \tag{8.6}$$

ΔT_m is calculated from indoor and outdoor temperatures, but ΔT_{im} is the daily variation of indoor temperature.

In warm climates, when cooling is required, ΔT_m should be reduced. The building thermal balance is positive; and because the interior temperature is higher than the outdoor temperature, $\Delta T_m > 0$. However, in some climates, it is possible to promote heat losses (Q_{ir}, Q_{ev}, Q_{cv}) to provide cooling, which would generate, through natural means, an average interior temperature that is lower than the average exterior temperature: $\Delta T_m < 0$. It is also recommended to reduce internal temperature swing (ΔT_{im}), which can be done by increasing building thermal inertia (thermal mass), and solar energy received and transmitted to the interior shading. The building ventilation regime should be adjusted so that ventilation is provided only when it cools the spaces inside.

In cold climates, the sum of all the values in the heat balance equation will tend to be lower than zero and the building thermal balance is negative because the interior temperature is lower than the outdoor temperature: $\Delta T_m < 0$. In these cases, it is necessary to promote heat gains through the windows and if possible through active systems in the walls and roofs (Q_{sw}, Q_c) to provide heating, which would generate, through natural means, an average interior temperature that is higher than the average exterior temperature: $\Delta T_m > 0$.

8.2 HEAT TRANSFER IN BUILDINGS

Heat exists in three different forms: (1) sensible heat (measurable with a thermometer), (2) latent heat (phase change of a material), and (3) radiant heat (a form of electromagnetic radiation).

8.2.1 Sensible Heat

Sensible heat is energy stored as the random motion of molecules; objects with more random motion have the most sensible heat. Sensible heat can be measured with a thermometer. The heat content of an object (amount of sensible heat) is a function of the temperature, the amount of mass, and the specific heat (C_p). More mass and a higher temperature indicate more sensible heat stored in the material. In Figure 8.5, the top two walls have the same amount of sensible heat because one has three times the temperature and one-third the mass. The bottom two walls also have the same amount of sensible heat because one wall has one-third the temperature but three times the mass as the other one. Because the heat is a form of energy, the SI unit for heat is J and the IP unit is Btu: 1 kJ = 0.9478 Btu.

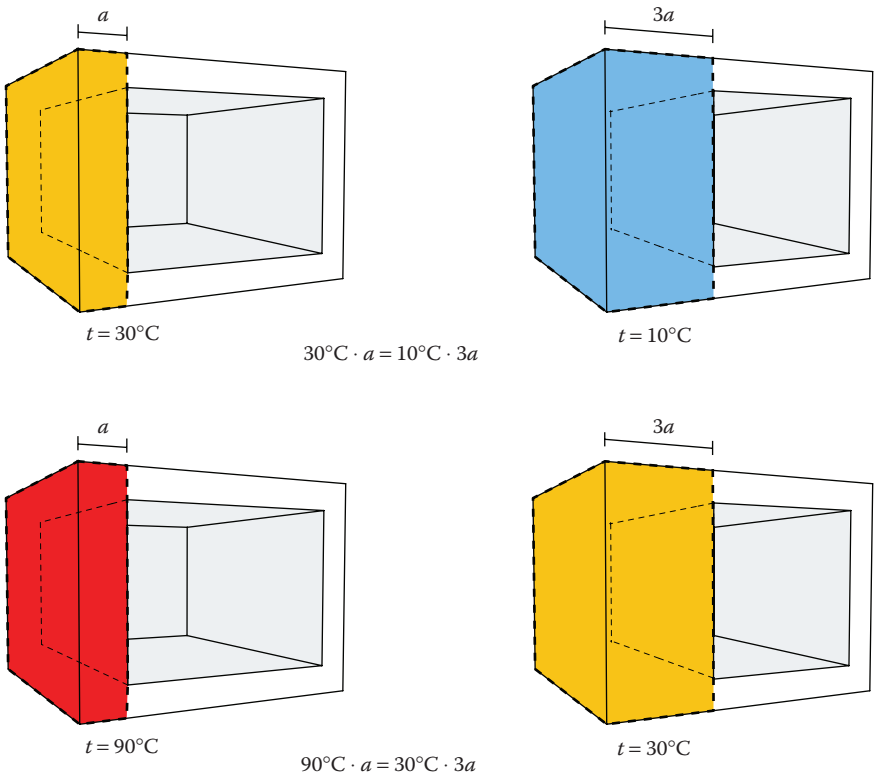


FIGURE 8.5 Relationship of heat content and mass with temperature.

8.2.2 Latent Heat

Latent heat is the energy required for a change of state of a material. This energy is released or absorbed by a substance during a change of phase (i.e., solid, liquid, or gas), also called a phase transition.

Adding 4.919 kJ to 1 kg water raises its temperature by 1°C; however, it takes about 2,260 kJ to evaporate 1 kg water (about 1,000 Btu/lb), which results in no change in temperature. This is because it takes a large amount of energy to break the molecular bonds necessary for a change of state. This heat energy cannot be measured with a thermometer, but it can be used to store and transfer heat, for example, in refrigeration cycles of mechanical equipment.

Latent heat of fusion (melting) is the phase change from solid to a liquid. When ice melts into water, sensible heat is changed into latent heat at a rate of 334 kJ/kg (144 Btu/lb). The ice absorbs this energy to melt; this process is called the latent heat of fusion (Figure 8.6). To change from a liquid to a solid (freeze), the water releases the same amount of energy that it needs to melt (Figure 8.7). Ice and water can exist in the same glass of water at 0°C (32°F) until all the ice has melted. After this point the water keeps on warming until it reaches room temperature.

Latent heat of evaporation (boiling) is the phase change of a liquid to a gas. When water evaporates, sensible heat is changed into latent heat at a rate of 2,260 kJ/kg (1,000 Btu/lb). To evaporate the water it absorbs energy (Figure 8.8), and to condense the vapor to water it releases energy (latent heat of vaporization) (Figure 8.9).

A phase change material (PCM) is capable of storing and releasing large amounts of energy when it changes from solid to liquid and vice versa, and they take advantage of this energy stored

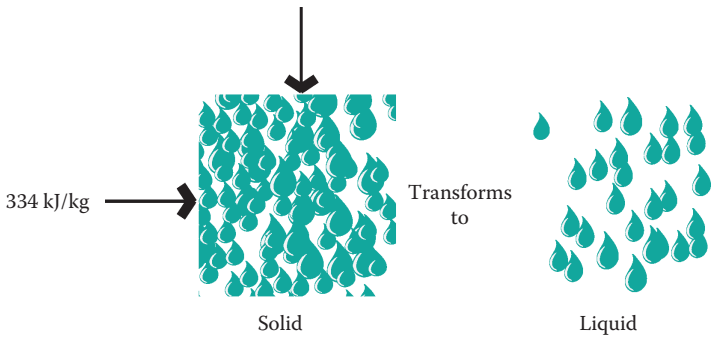


FIGURE 8.6 Phase change from a solid to a liquid.

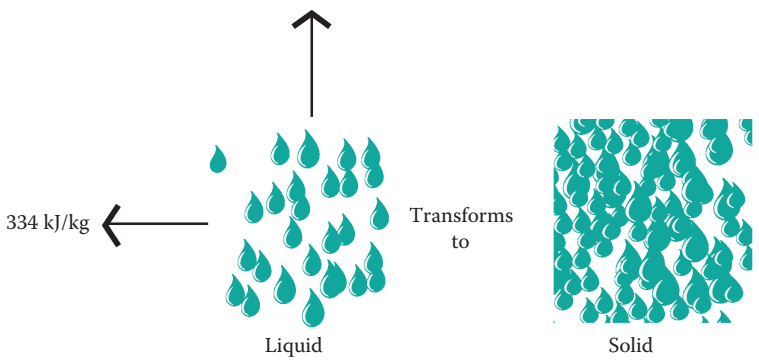


FIGURE 8.7 Phase change from a liquid to a solid.

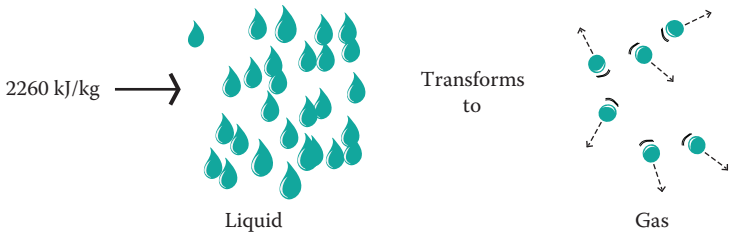


FIGURE 8.8 Phase change from a liquid to a gas.

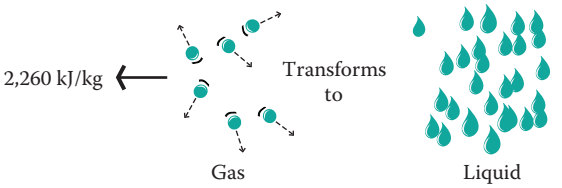


FIGURE 8.9 Phase change from a gas to a liquid.

and released during the phase change of state of a material to stabilize the air temperature of a space. If the ambient temperature in a space with a PCM rises, the temperature of a solid PCM rises as it absorbs heat around it. When it reaches the phase change temperature it will begin to melt and absorb a large amount of heat at an almost constant temperature. The PCM continues to absorb heat without a significant rise in temperature until all of it is transformed into a liquid. When the ambient temperature around the liquid PCM falls, it releases its stored latent heat as it begins to solidify. A PCM can be designed to change phase at almost any temperature between –5°C and 190°C, and it is very useful in architectural applications if it is designed to change phase close to the comfort zone, reducing the indoor temperature swing, absorbing and releasing energy while it reduces the indoor air temperature swing, and providing the same effect as thermal mass without the bulk. Phase change materials are usually made of a paraffin, fatty acids, or salt hydrates. There are many brands that produce different types of PCM that come in different forms, usually encapsulated in some form, in pouches that can be placed in different locations in the building, or integrated with building materials such as drywall, windows, concrete, and insulation.

8.2.3 Radiant Heat

Radiation is a net transfer of heat from a warmer object to a cooler one by means of electromagnetic waves through space. This transfer of heat occurs in the portion of the electromagnetic spectrum called infrared. All bodies with a temperature above absolute zero radiate energy, so whenever the object faces an air space or a vacuum it will exchange energy with its surrounding surfaces. Hot bodies lose heat by radiation because they emit more energy than they absorb. Radiation is not affected by gravity, and therefore a body can radiate equally in all directions. Thermal radiation can be concentrated in a small spot using mirrors.

8.3 HEAT TRANSFER BY CONDUCTION

Conduction is the process of heat transfer in a solid or a fluid at rest by a direct molecular interaction between adjacent molecules. When two objects come into contact, some of their random motion will be transferred from the hotter, more rapidly moving objects (atom or molecule) to the cooler, slower objects (Figure 8.10). Conduction occurs only when the molecules are close enough

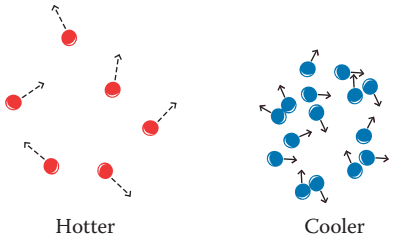


FIGURE 8.10 Heat as a function of random motion.

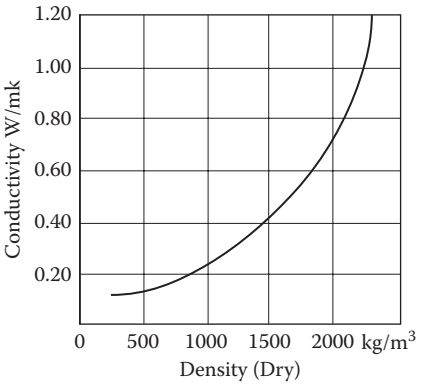


FIGURE 8.11 Relationship between mass and conductivity.

to collide, which is why air is not a good heat conductor and vacuum is not a heat conductor at all. In general, conductivity is related to the density of the material, and materials with higher density are more conductive (Figure 8.11).

Conduction requires a temperature difference between both sides of the surface, when it is a wall or a building component, or between the solids that are in contact. Heat always flows from a high to low temperature; and if there is no difference in temperature, then there is no flow of energy by conduction (Figure 8.11).

Some characteristics of materials that affect conduction are conductivity, conductance, resistance, and thermal capacity. A concept that defines the overall conductive capacity of a building component composed of several layers is the thermal transmittance or *U*-value. Two additional factors that define the conductive performance of a material in the building are time lag and decrement factor.

8.3.1 Conductivity

Thermal conductivity is a characteristic of the material that indicates its capacity to transmit heat flow. A material with a high conductivity will allow more energy flow. It is expressed in (W/m °C) or (Btu-in/h ft^2 °F) and is defined as the rate at which heat will flow through a homogeneous material per unit of thickness. In SI units, it is defined as the rate at which watts flow through 1 square meter when the temperature difference is 1°C, and in IP units it is the number of Btu/h that flow through 1 square foot of material, 1 in. thick, when the temperature drop through this material is 1°F (under conditions of steady heat flow). As already discussed, materials with higher densities usually have higher conductivities. Table 8.3 shows the conductivity of some materials. More materials can be found in many sources, including ASHRAE's *Handbook of Fundamentals.*

TABLE 8.3
Conductivities of Some Materials

Good Conductors (W/m °C)	
Copper	280
Steel	52
Aluminum	165
Construction steel	60
Conductors	
Heavy rock	3
Common concrete	2.1
Compressed earth	1
Poor Conductors	
Concrete with light aggregate	0.14–0.27
Glass	0.8
Wood	0.13–0.2
Insulators	
Mineral wool	0.03–0.05
Polystyrene	0.03–0.05

8.3.2 Conductance

Whereas conductivity is a property of the material independent of its shape or size, conductance is a property of a body of given thickness. It is the rate of heat flow through a homogeneous material (or combination) of a stated thickness and is measured in W/m^2 °C or Btu/hr ft^2 °F. Conductance is useful for materials that come in standard thicknesses.

8.3.3 Resistance

The resistance (R) is the reciprocal of conductance and is a much more commonly used value expressed in m^2 K/W or ft^2 °F hr/Btu. It is a measure of the resistance of materials and air spaces to the flow of heat by conduction, convection, and radiation, and it measures the insulating value. The lower the R value, the lower the resistance of the material to the flow of heat; for example, R14 means that the material would transfer 1/14 Btu/hr/ ft^2/ °F of temperature difference. All materials offer some resistance to the flow of heat; however, an insulating material will be thousands of times more resistant to the flow of heat than a conductive material, which means that it can be thousands of times thinner.

$$R = \frac{b}{\lambda} \quad \text{or} \quad R = \frac{k}{e} \tag{8.7}$$

where:
R is the resistance
$\lambda = k$ is the conductivity
$b = e$ is the thickness

Air is usually the best resistor for heat flow in a building, but the resistance of the air space is not proportional to its thickness. After about 40 mm, the resistance to the heat flow will remain relatively constant; therefore, making an air space larger than 40 mm does not have much effect. The optimal thickness for an air cavity is about 4 cm (a little less than 2 in.). Surfaces that consist of polished materials (low

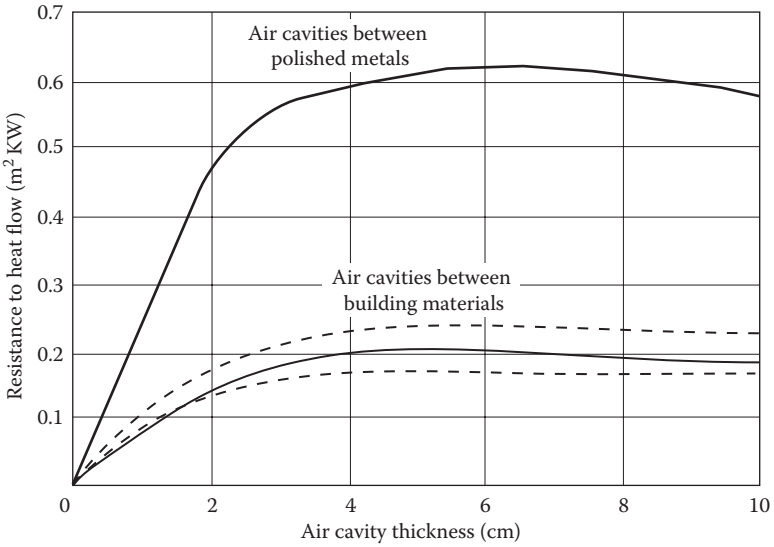


FIGURE 8.12 Resistance of an air space as a function of thickness and surface emissivity.

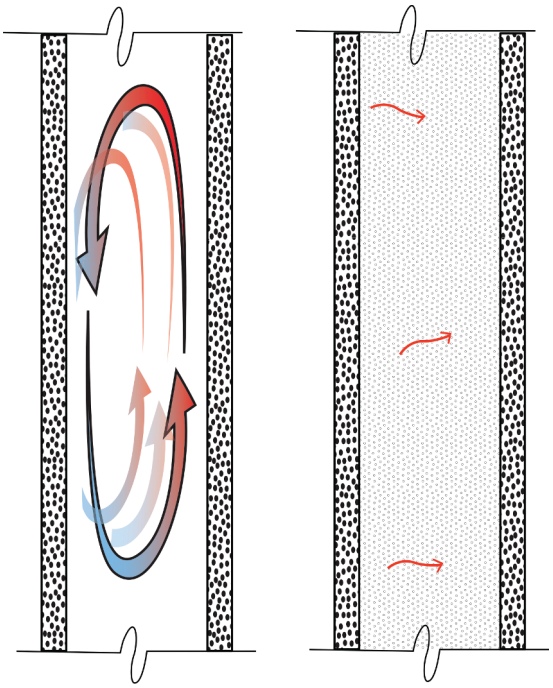


FIGURE 8.13 Heat transfer by convection through an air space on the left and blocked by loose material on the right.

emissivity) facing an airspace provide much better resistance than typical construction materials. If the cavity is larger, then convective currents can occur inside it, increasing heat transfer by convection (Figure 8.12). These convection air currents can be reduced or eliminated by adding lightweight elements inside the cavity that still maintain air in most of the cavity but block convective air currents. For example, a loose tangle of mineral fibers in a wall prevents the air from circulating (Figure 8.13). Thermal resistance of air spaces will also vary depending on the direction of the heat flow.

8.3.4 Thermal Transmittance (*U*-Value)

The thermal transmittance of an element is the total conductance of a building element and is the inverse of the sum of all the resistances including external and internal air layers.

The *U*-value is a number that is an expression of the steady-state rate at which heat flows through architectural skin elements. It is measured in W/m^2 K or Btu/hr ft^2 °F.

$$U = \frac{1}{\Sigma R} \tag{8.8}$$

The inner and outer surfaces of a material also offer some resistance to the heat flow (R_{si} and R_{so}, respectively). The reciprocal of these are inner and outer surface conductance (h_i and h_o, respectively) and include convective and radiant components: $h = h_r + h_c$. The degree of surface conductance depends on the position of the surface, the direction of the heat flow, and air movement. Surface resistances should be considered in the calculation of the *U*-values.

The heat flow through a building's envelope always takes place from warmer surfaces to cooler surfaces and can be from exterior to interior or interior to exterior depending on the temperatures. Therefore, to determine the heat flow, the resistance of the different layers of the wall must be added to the surface resistance, or air-to-air resistance ($R_a - a$). The inverse value of the air-to-air resistance is called the thermal transmittance coefficient (U), and its unit is W/m^2 °C (Figure 8.14). Thermal transmittance is the value that best defines the amount of heat that can be transmitted through a component of the building, and low *U*-values block more heat than high *U*-values.

$$R_a - a = R_{si} + \Sigma R_m + R_{so} \tag{8.9}$$

where R_m is the resistance of material

$$U = (R_a - a)^{-1} \tag{8.10}$$

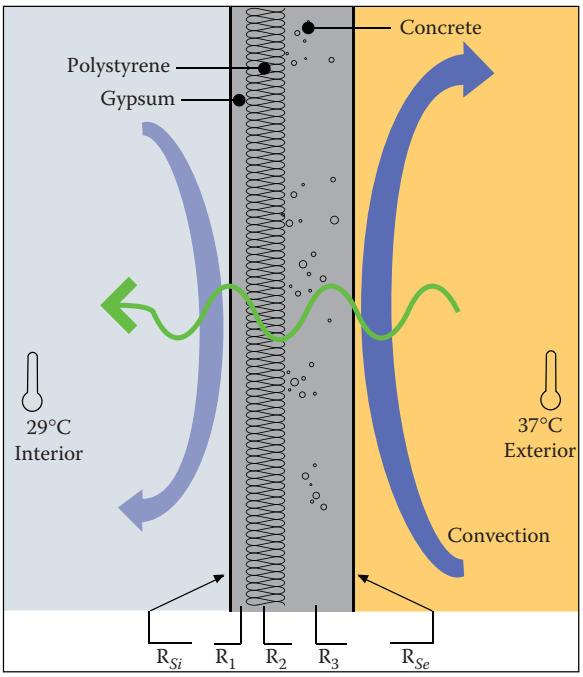


FIGURE 8.14 Thermal transmittance or *U*-value.

TABLE 8.4
Thermal Capacity of Several Common Materials per Unit Mass and per Unit Volume

	Per Unit Mass		Per Unit Volume	
	Btu/lb °F	kJ/kg °C	BTU/ft_3 °F	kJ/m_3 °C
Water	1	4.19	62	4160
Steel	0.12	0.5	59	3960
Stone	0.21	0.88	36	2415
Concrete	0.21	0.88	31	2080
Brick	0.2	0.84	25	1680
Clay soil	0.2	0.84	20	1350
Wood	0.45	1.89	14	940
Mineral wc	0.2	0.84	0.4	27

8.3.5 Heat Capacity and Specific Heat Capacity

The heat capacity of a system is the amount of heat required to change the temperature of a whole system by 1°C. Specific heat capacity is defined as the amount of heat required to raise the temperature of a unit volume or unit mass of a material by one unit of temperature. In the SI units, heat capacity is expressed in units of joule(s) (J) per kelvin (K) per unit mass (kJ/kg K). It is also expressed in kJ/kg °C or Btu/lb °F (Table 8.4). It is roughly proportional to the density of the material, with denser materials typically having a higher specific heat capacity than materials with lower density. An important exception is water, which stores much more heat per unit weight than concrete, which is denser. Buildings with massive structures and high heat capacities will act as heat sinks, absorbing and storing heat from the interior of the space (Figure 8.15).

8.3.6 Time Lag

Time lag is the delay in the heat flow measured in units of time (e.g., hours). It is the length of time from the moment when the outdoor reaches the maximum temperature and the indoor reaches the maximum temperature (Figure 8.16). The time lag is affected by the thermal capacity of the material; more massive materials usually generate a larger time lag (Figure 8.17). For example, concrete with a thickness of 30 cm and a density of 1,600 kg/m^3 has a time lag of 10 hours.

8.3.7 Decrement Factor

The decrement factor is calculated by dividing the indoor swing by the outdoor swing; thus, a building with a smaller decrement factor has a larger difference between these swings. Heavy mass buildings have a smaller decrement factor because they reduce the indoor temperature swing as a function of the thermal mass (Figure 8.18).

$$DF = \frac{IS}{OS} \tag{8.11}$$

where:
DF is the decrement factor
IS is the indoor swing
OS is the outdoor swing

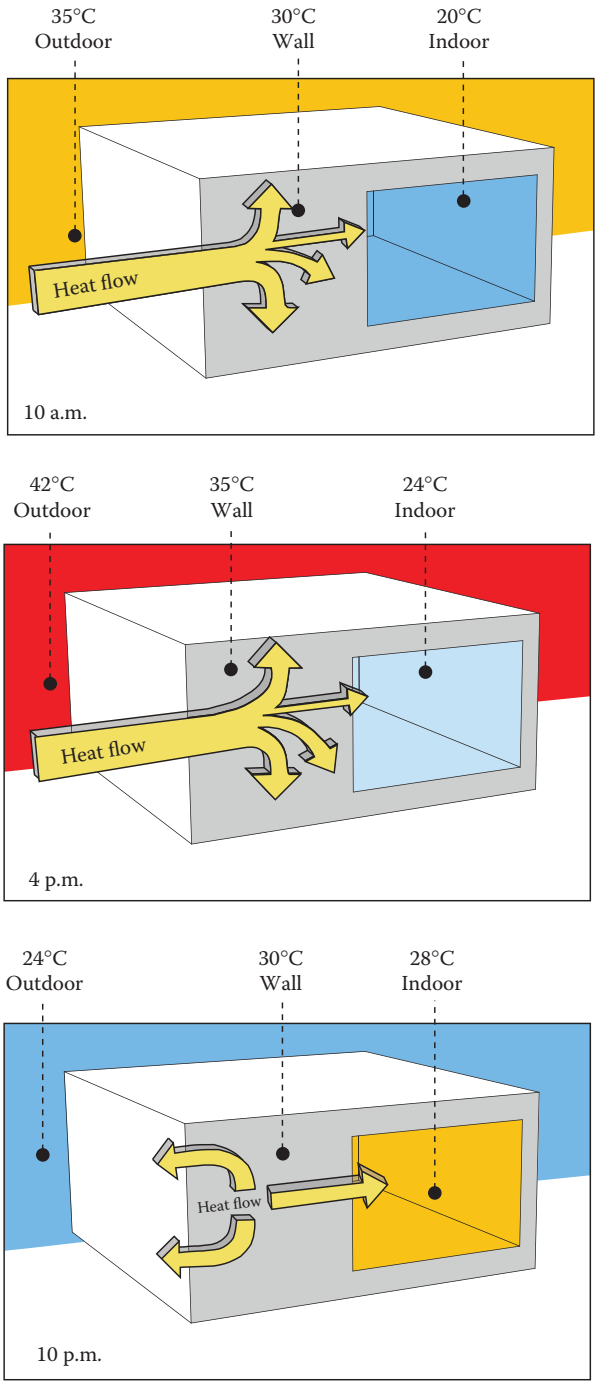


FIGURE 8.15 Thermal mass acting like an insulator.

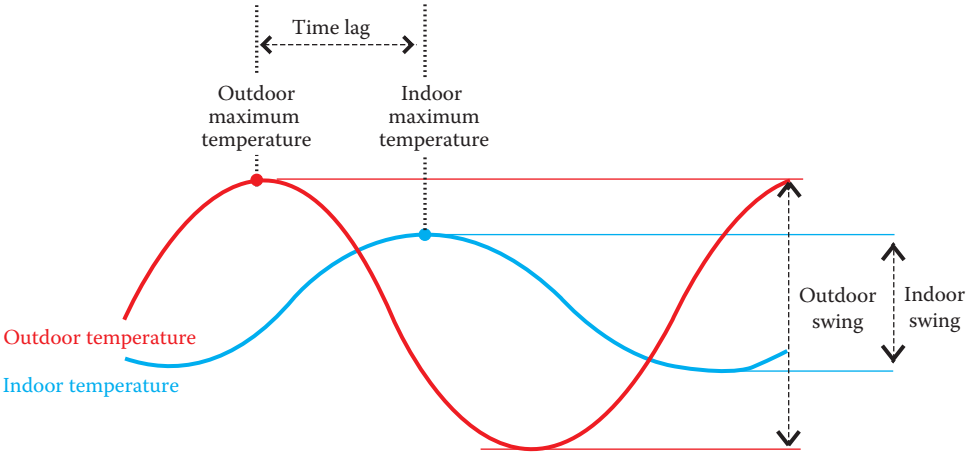


FIGURE 8.16 Time lag.

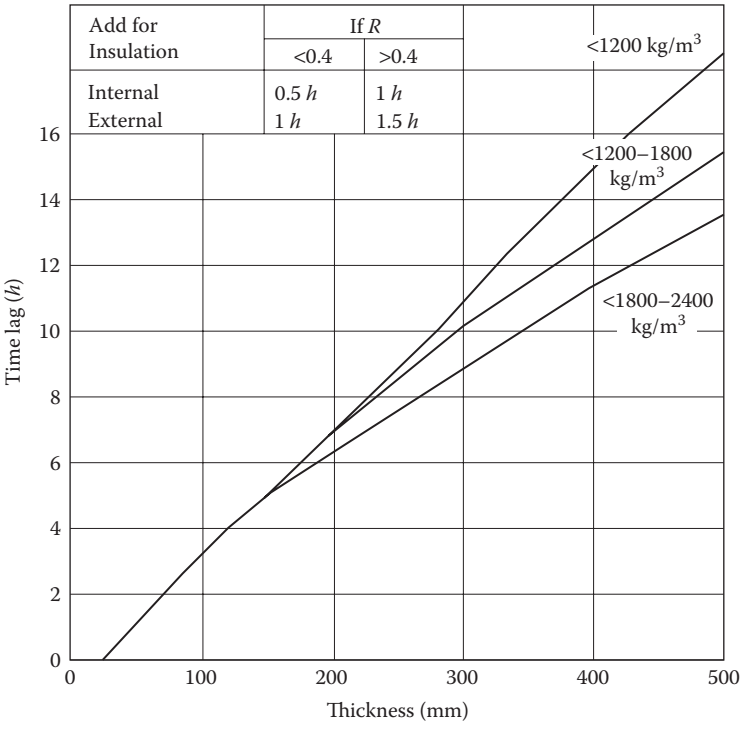


FIGURE 8.17 Time lag as a function of density and thickness.

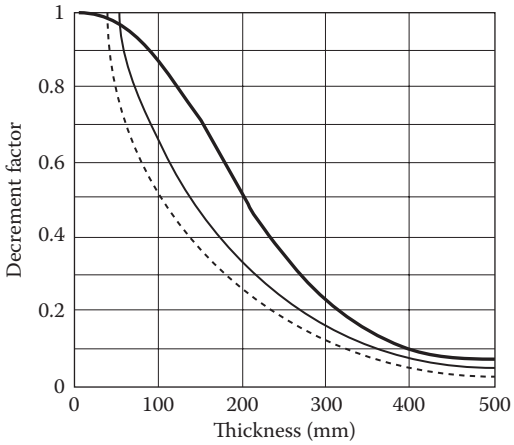


FIGURE 8.18 Decrement factor as a function of density and thickness.

TABLE 8.5
Resistances and Time Lags of Different Materials

Time Lag	Resistance	Thermal Storage	Materials
Low	Low	High	Metal
High	Low	High	Concrete
Low	High	Low	Styrofoam

The thermal transmittance of a material is not the only factor that affects thermal behavior. Many combinations of materials in walls can give the same *U*-value but different mass or even the same amount of mass and with mass location and thermal transmittance in different parts of the wall, which affects thermal behavior (Table 8.5).

8.3.8 Heat Flow by Conduction

In an opaque material, heat flow by conduction takes place directly between adjacent particles of the material when molecules transfer heat from hotter to colder molecules through its higher molecular movement. The rate of heat flow in one homogeneous layer varies from one material to another, and, in absence of solar radiation, it is defined by Fourier's Equation 8.12. It depends on the thermal conductivity of the material, its width, area, and the temperature difference between both faces of the surface:

$$Q = \lambda \times e^{-1} \times A \times \Delta t \tag{8.12}$$

where:

Q is the heat flow rate or simply flux rate; the total flux in unit of time through a definite surface of material or space, in J/s units, which is the same as watts (W); in IP units, it is Btu/hr

λ is the thermal conductivity of the material (W/m°C)

e is the thickness of the material (m)

A is the enclosure surface or area through which heat can be transmitted; it is perpendicular to the heat flow (m^2)

Δt is the temperature difference between the two faces of the surface. In the case of a building's envelope, it is the difference between the external and internal surfaces. If there is no solar radiation, it is assumed that both faces of the surface will have the same temperature as the air (°C)

Fourier's equation can be used to determine heat flow by conduction (Equations 8.12 and 8.13). The heat flow is proportional to the thermal transmittance of the material, the area, and the difference in temperature. Appropriate color treatment of exterior surfaces to reduce the incidence of solar radiation can have a positive effect on the reduction of the total heat flow inside the building. This is discussed later in the section on radiation.

The Fourier equation can also be expressed as

$$Q = U \times A \times \Delta t \tag{8.13}$$

where:

Q is the heat flow rate or heat flux (W) (Btu/hr)
U is the thermal transmittance of the element (W/m²K) (Btu/hr ft² °F)
A is the area through which heat is transmitted (m^2) (ft^2)
Δt is the temperature difference between the two faces of the surface (°C) (°F)

The application of the design strategies can also be affected by other factors such as the use of the space (daytime, nighttime, or both), air change rate, climatization (natural or mechanical), air humidity, air temperature, and radiation.

In buildings with exterior temperatures close to thermal comfort, insulation is not critical unless radiation affects the building in an important way. In well-ventilated buildings in warm climates with an envelope that is well protected from solar radiation (exterior surface temperature equal to air temperature), thermal insulation will not fulfill any function because indoor temperature could be quite close to outdoor temperature ($\Delta t = 0$). Therefore, heat flow by conduction between the exterior and interior will be very small. In cool climates with outdoor temperatures slightly below the comfort zone, insulation is also not very important because internal gains and heat gains by radiation will usually provide sufficient gains to offset the losses by conduction.

When there is a significant temperature difference between the indoor and the outdoor of the building (at least above 4°C), it is recommended to begin reducing heat flow by conduction. In naturally ventilated buildings, this difference can be the result of daily temperature swings, variations in ventilation flow, or the incidence of diffuse or direct radiation. Insulation is more important in buildings with mechanical heating or cooling, where indoor temperatures are farther away from outdoor temperatures, usually above 6°C in air-conditioned buildings and 10°C in heated buildings and where surface temperature is significantly affected by solar radiation. In these cases, insulation is important to reduce heat gains or losses, which would increase the load on the mechanical cooling equipment.

8.3.8.1 Use of Insulating Material in Walls, Ceilings, and Floors

The first important design principle to reduce heat flow by conduction through the envelope is to use insulating materials with low conductivity and high resistivity. Heat flow is directly proportional to conductivity; a material with a conductivity 50% lower than another material will reduce heat flow by 50%.

Conductivity generally increases with density. Dense materials, such as metals, are more conductive than light materials, such as polystyrene. Air or materials with air have low conductivity, as long as the air is relatively still without major convective air exchanges. The presence of humidity in the material also increases thermal conductivity, because the higher the water content, the larger the amount of molecules in movement. Materials with water in them lose many of their insulating properties.

Some construction materials or building assemblies are made of several components or of several components and air. For example, in a perforated cement or clay brick, the equivalent conductivity is calculated taking into account the proportion of air it contains and the thermal resistance of its material.

In walls, and especially in roofs, combinations of materials that generate structural resistance and insulating capacity must be used. By using layers of insulating materials, good *U*-values can be obtained with relatively thin widths. It is especially important to control thermal gain in components receiving high solar radiation, such as roofs in low latitudes.

Zold and Szokolay (1997) classified insulating materials according to how they controlled heat: Reflective, Resistive, and Capacitive insulators. Reflective insulators face an air space and are better at blocking heat transfer by radiation. They must have a low absorptivity and low emissivity (e.g., foil backing on batt insulation). Resistive insulators are those that insulate depending on their width and resistance value. Capacitive insulators act as a function of their width and their density; they have a retarding effect on heat flow and are discussed later.

8.3.8.2 Use of Air Spaces in Walls, Ceilings, and Floors

Density is related to conductivity (Figure 8.11); the materials with the highest densities usually have the highest conductivities. Air, the element with the lowest density and conductivity, is one of the best insulators and is also the cheapest; therefore, it is recommended as one of the layers of a multilayer building assembly, roof, floor, or wall. However, heat flow in these air spaces occurs in several forms: Heat reaches the wall of the air space by conduction and then is transmitted to the other wall by convection and radiation. These air spaces can be ventilated to reduce heat flow by convection, such as in a ventilated attic if the heat flow is downward, otherwise it increases heat flow. To reduce heat flow due to radiation, a reflective or radiant barrier should be installed.

8.3.8.3 Increase the Outer Surface Resistance of Walls and Roofs

The surface of a material also offers resistance to the heat flow, and this superficial resistance depends on its radiative and convective component. The amount of surface resistance depends on the position of the surface, the direction of the heat flow, and the velocity of air. Surface resistance is usually higher in horizontal elements, when the heat flows downward, and when air velocity is lower. It is possible to modify these parameters in the element's surface (e.g., changes in smoothness, texture, and inclinations) and thus to increase the resistance of the material, reducing its *U*-value.

8.3.8.4 Increase Thermal Resistance of Windows

The heat flow through a window exposed to the sun is mainly by radiation and is affected by the angle of incidence of the solar rays and the type of glazing. However, because windows are also objects of solid molecular composition, there is also heat flow by conduction, which can be more or less important depending on the thermal resistance of the window, and the temperature difference between the indoors and the outdoors.

Windows with high resistances are more important when the building is heated or cooled mechanically and there is a larger temperature difference between the indoors and the outdoors, increasing the heat transfer by conduction. It is important that the glazing system does not block solar radiation in a cold climate, because this radiation can be used for passive heating in the winter.

Currently there are many types of advanced window glazing systems, and their discussion would warrant many pages. Figure 8.19 shows approximate thermal transmittance ranges for different types of windows. To improve thermal resistance, manufacturers usually implement one of these three strategies:

1. Two or more layers of glass with air spaces or with other gases to act as insulators
2. Special coatings that control the amount of solar radiation and thus the amount of heat that is absorbed and transmitted by conduction (and of course by radiation, which is much more significant)
3. Operable elements such as shutters, curtains, or blinds, sometimes inside the window

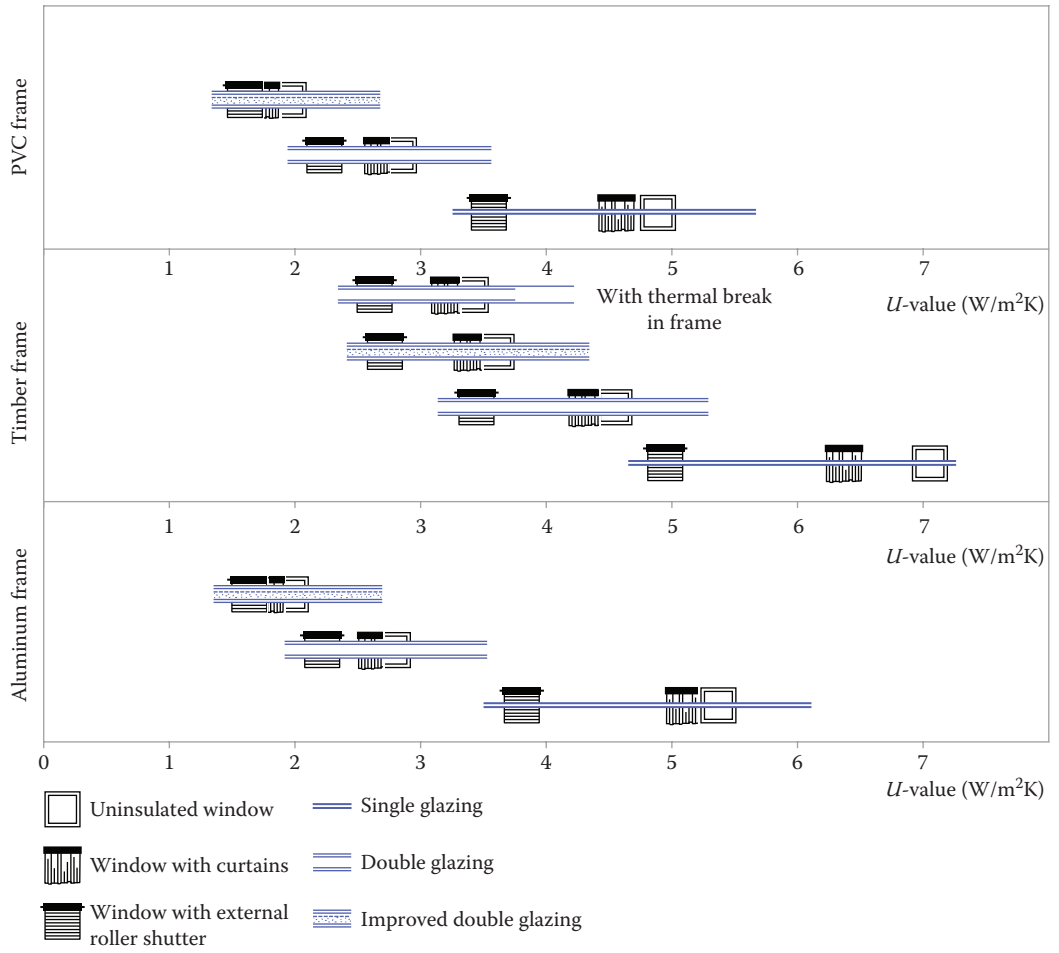


FIGURE 8.19 Thermal transmittance of different window types.

8.3.8.5 Use of the Thickness of the Architectural Elements as a Regulator of the Building's Indoor Temperature

When the thickness of the material increases, the resistance of the component to the heat flow also increases. However, this increase in thickness has a practical limit due to costs and feasibility of construction. It is much more practical and efficient to use insulating materials rather than regular construction materials to block the heat flow. However, insulating materials have a low density and, therefore, a low structural resistance and should be used in combination with other construction materials that give them rigidity; thus, the need arises for the development of multilayered walls.

8.3.8.6 Energy Storage Capacity of Materials

Not only does the increase in the material's thickness affect its resistance to the heat flow, as indicated by the very simplified steady-state model, as buildings are not necessarily subject to constant flows of energy; it is also more likely for these flows to vary periodically, generally as a function of the daily 24-hour period, causing a regime of dynamic, nonstatic behavior. By contrast, all building components have a certain heat storage capacity and can therefore accept energy during the heating process that will be released later during the cooling process, creating a thermal delay and affecting the decrement factor.

The heat storage capacity of a material depends on its mass and therefore on its density and specific heat. The thermal energy stored in a material can be determined with Equation 8.14, where the capacity to store energy is directly proportional to the specific heat of the construction component, its width, and the temperature difference between the material and the surrounding temperature:

$$Q = c \times p \times V \times \Delta t \tag{8.14}$$

where:

Q is the thermal energy stored
c is the specific heat (Wh/kg °C)
p is the density (kg/m^3)
V is the volume (m^3)
Δt is the temperature difference between the material and surrounding air

Two materials with the same conductivity but different specific heat and density, subject to a constant heat flow, will permit the same heat flow to the interior of the building. However, if the heat flow conditions are periodical, such as in a 24-hour cycle, there can be important differences between the maximum inner values and the moment in which these occur. Therefore, two walls exposed to the same heat flow but with different densities can produce important differences in their indoor swings and thermal delays, even though the average daily heat flow will be the same.

If there is little difference in the maximum and minimum temperature values between day and night, the material will not be able to absorb a lot of energy. Therefore, materials with high thermal capacities are not very useful in areas with thermal swings below 8°C, such as in hot and humid climates, and most of its mass is wasted. However, in locations with higher daily temperature swings, these materials will help to reduce the outer temperature curve through this process of energy absorption and emission. Thus, the swing is reduced. The use of thermal mass as a heat sink is very important in most passive heating and cooling systems and is discussed in the following section.

8.3.8.7 Reduce the Temperature Swing Using Materials with High Density and Thermal Capacity

The delay and reduction of thermal swings inside the space creates temperature differences that can be used to cool or heat up a space. When temperature differences between the indoors and the outdoors are high, with both extremes out of the thermal comfort zone (one above and one below), thermal mass can be used to reduce swing and generate indoor values close to a halfway point that can be closer to the comfort zone.

A material with a high specific heat and density, such as cement, will store much more energy than a light insulating material; therefore, this material will need to absorb much more energy for the same temperature change and will also release much more energy for the same temperature variation. For example, a concrete wall 30 cm wide will need 2 kWh/m^2 to increase from 10°C to 20°C, whereas the temperature of an insulating material will increase the same number of degrees with only 0.04 KWh/m^2 (Bansal, Hauser, and Minke, 1994).

It is necessary to know how much mass to use. Most authors use a rule of thumb of about 10 cm (4 in.) of useful thickness of thermal mass for a daily cycle. This useful thickness is the depth of penetration of the heat flow, which refers to the depth that temperature oscillations reach during the processes of energy storage and release and depends on the period; the bigger this is, the larger the thickness of the element. This depth of penetration can be calculated mathematically in many ways, but according to Zold and Szokolay (1997) it can also be calculated with a rule of thumb in which the lowest of the following values is chosen:

1. Half the total thickness of the construction
2. 100 mm
3. The width from the layer in question to the first insulating layer

8.3.8.8 Reducing the Surface Area of the Building

The form factor, sometimes called the skin-to-volume ratio, is used to determine the energy exchange surfaces. It is the relation between the surfaces of the walls directly in contact with the exterior and the interior volume. The ground surface, walls in contact with another building, or walls buried more than 1 meter deep are usually not included because they are not exchanging energy directly with the outdoors. The form factor can be calculated using

$$F = \frac{\text{SE}}{V} \tag{8.15}$$

where:
F is the form factor
SE is the exterior surface area
V is the interior volume

Volumetric loss (G) due to heat transfer through walls is the product of the form factor multiplied by the mean thermal transfer coefficient of the envelope, and represents the insulating level of the building envelope. It is a number that is used in many energy codes to describe the thermal losses through the building skin. To determine this coefficient, losses due to air renovation should be considered; however, only morphological variables are discussed here. Thus, we have

$$G = \frac{\text{SE}}{V} \times U \tag{8.16}$$

$$G = F \times U \tag{8.17}$$

Greater compactness means less contact with outdoor conditions and in the winter reduced possibilities for heat gain by solar radiation but also reduced opportunities for heat loss. A compact form is appropriate for hot and dry climates, where a compact exterior envelope reduces the amount of incident solar radiation flowing toward the interior of the building.

In buildings that are not mechanically cooled, located in warm and humid locations where ventilation is the most effective mechanism to reduce the psychological effect of high humidity, a compact form is typically not the best solution because extended arrangements provide more opportunities for air movement than compact building forms (Figure 8.20). Once the building is subject to

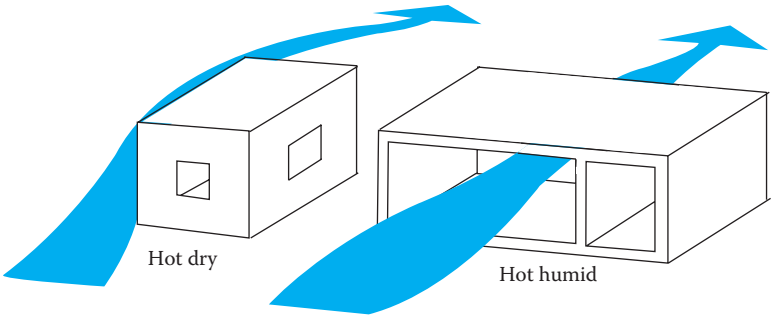


FIGURE 8.20 A compact form is better for a hot and dry climate while an extended form is better in a hot and humid climate.

cross-ventilation during daytime hours, its interior temperature tends to follow the exterior pattern, reducing the temperature difference between the interior and exterior and the heat flow through the envelope. Because of this a large surface area does not significantly affect the interior temperature during the day. At sunset and night hours when the winds usually calm down, the bigger area of the envelope allows faster cooling.

If the interior habitable space is air-conditioned with mechanical equipment and if the exterior surface is exposed to the rays of the sun, the volume should be compact to provide more efficient cooling by reducing the surface area exposed to the outside. This is not as important in a superinsulated building or in a milder climate.

In rooms ventilated with passive cooling systems, the volumetric response will depend on the requirements of the adopted system. For systems that store heat, a compact design would be more convenient, but those based on natural convective principles, as night ventilation or passive heating, usually have better performance with a large interior surface more exposed to the indoor air.

In a cold climate, it is even more important to reduce the surface area of the building to minimize conductive heat losses to the outside. Reducing the surface area in contact with the outdoors reduces the amount of energy exchanged to the outdoors, and the most efficient way to do this is to minimize the outside wall and roof areas and thus the surface-to-volume ratio. The sphere is the surface that encloses the most space with the least surface area, and this is probably one of the reasons many early civilizations created dome-like surfaces to protect themselves from the cold elements. Of course, many of these traditional buildings did not have passive solar heating systems and instead had a simple central source of heat such as a fireplace (Figure 8.21). If passive heating was implemented, it would affect the building form; maybe the skin is expanded where it captured solar radiation for passive solar and is minimized where it did not (Figure 8.21). Also, if the building is very well insulated and the climate is milder, with a smaller difference between the interior and the exterior the form factor becomes a less significant consideration.

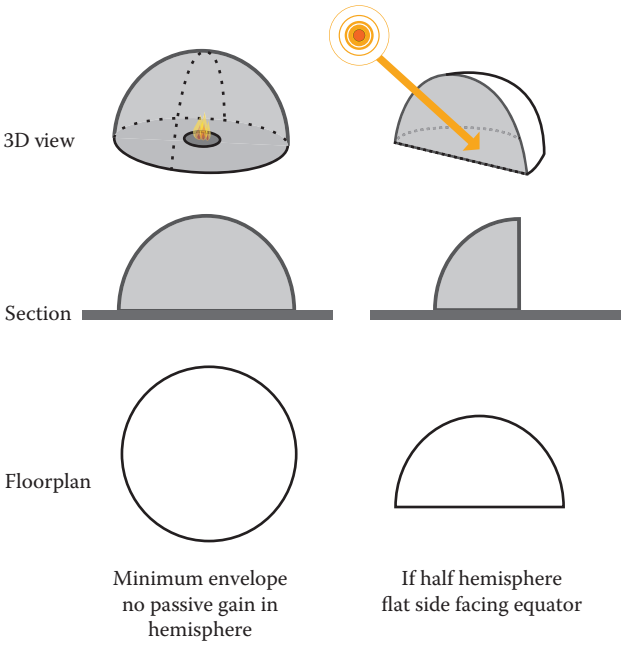


FIGURE 8.21 An ideal form in a cold climate should be compact with the possibility of passive solar gain.

8.4 HEAT TRANSFER BY RADIATION

8.4.1 Concepts

Is the process of heat transfer by means of electromagnetic waves. Any two objects that can see each other through a medium that is transparent to light, such as air or vacuum, exchange radiant energy. This exchange can be easily blocked when an opaque object is placed in the path of the rays. Objects at room temperature emit energy in the infrared, and when they are hot enough to glow, they radiate energy in the visible part of the spectrum. Hot bodies lose heat by radiation because they emit more energy than they absorb. The wavelength of the radiation is inversely proportional to the temperature. Higher temperatures have lower wavelengths.

Heat flow by radiation is not affected by gravity; therefore, a body will radiate energy in all directions, is proportional to temperature, is affected by the viewing angle, does not require contact or a medium of transfer, is affected by the surface properties of building materials, is affected by the opacity or transparency of an object, and travels at the speed of light through an empty space.

These radiant exchanges are important because they also affect thermal comfort. Even though these surfaces are not in direct contact with our body, they affect our perception of temperature. One of the indicators of this effect is the mean radiant temperature (MRT), which is the weighted mean temperature of all the objects surrounding the body. It is an average of the temperature of each of the surrounding surfaces, weighted according to the spherical angle and the thermal emissivity of each surface, and is positive if the objects are warmer than the skin and negative when they are colder. The MRT is usually measured with a globe thermometer, which consists of a dry-bulb thermometer encased in a 150 mm diameter matte black copper sphere with an absorptivity close to that of the skin. This measurement is useful to determine the effects of radiation on thermal comfort and is an important parameter governing human energy balance because these radiant exchanges affect the temperature of skin, which has a high emissivity and absorptivity of about 0.97.

We can raise the MRT in a cold climate by implementing several strategies: (1) allow the sun to penetrate, which is usually easy to do and free; (2) improve thermal insulation and permit the heating system to warm the surfaces to a higher temperature; (3) install highly reflective surfaces so that they reflect heat back to the body; (4) heat very large surfaces to temperatures a few degrees above the skin temperature; or (5) heat small surfaces to temperatures hundreds of degrees above the skin temperature.

8.4.2 Factors That Affect Solar Radiation

Radiation is affected not by gravity but by the radiative properties of the material with which it interacts, which are affected by the surface of the material. Several surface properties affect radiation: absorptance or absorptivity (a), reflectance or reflectivity (r), emittance or emissivity (e), and transmittance.

Absorptance is a surface quality that indicates the proportion of the radiation absorbed by the material. This radiation is converted into sensible heat within the material, thus raising its temperature (Figure 8.22). Reflectance is a surface quality that indicates the proportion of the radiation that bounces off the material, leaving the temperature of the material unchanged. The reflectance indicates the ability of a surface to reflect solar radiation (Figure 8.22).

Absorptance and reflectance are expressed as decimal ratios as a fraction of the perfect absorber. For example, an absorptivity of 0.74 indicates that 74% of the radiation is absorbed. The sum of the absorptivity and reflectivity of an opaque surface is a unit; whatever is not absorbed is reflected.

Emittance or emissivity is a measure of the ability of a surface to radiate (emit) electromagnetic radiation through the surface, reducing the sensible heat content of the object. It is also compared to a black body, which is the perfect emitter (Figure 8.23). Polished metal surfaces have low emittances, and most other materials have high emittance. Emissivity and absorptivity are not

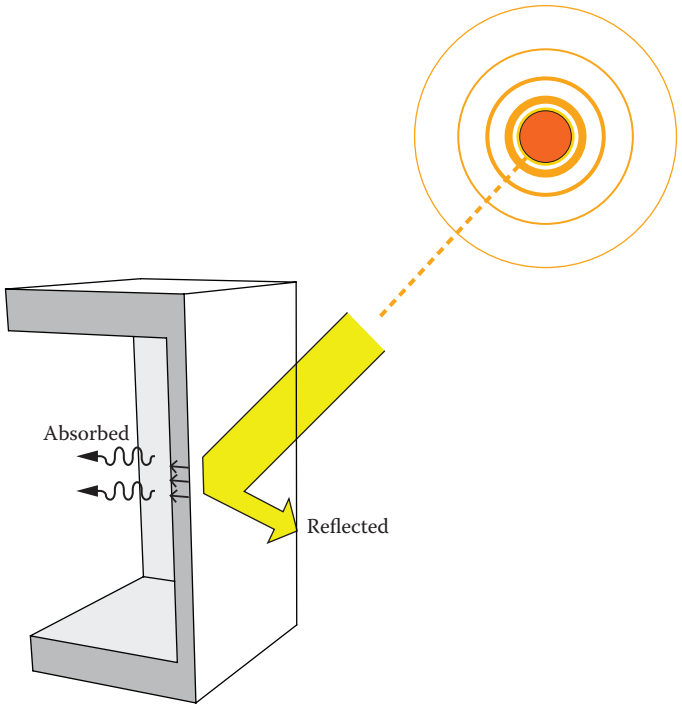


FIGURE 8.22 Absorptance and reflectance.

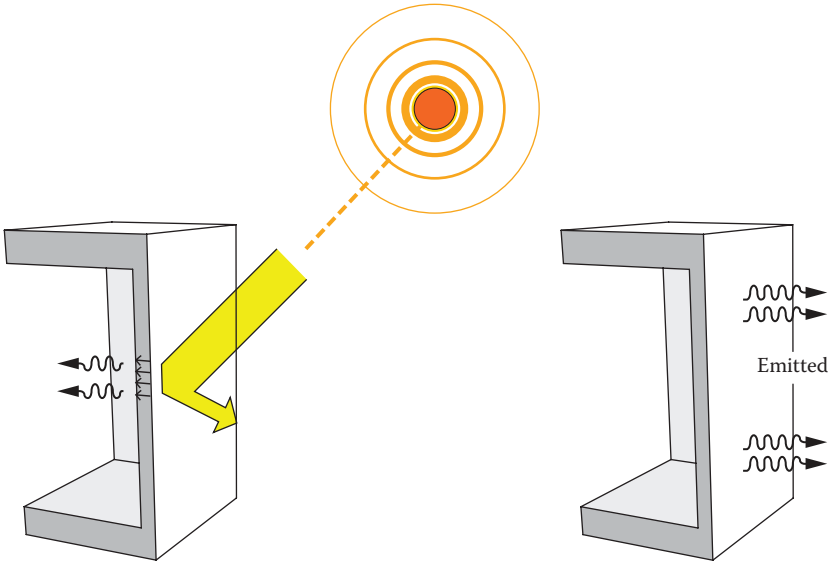


FIGURE 8.23 Emittance.

necessarily proportional across different wavelengths. How they relate in a material affects its heat gain by radiation (sensible heat content) and its temperature.

Most materials have an absorptivity equal to emissivity at the same temperature or wavelength; however, some materials have selective properties and absorb or emit energy differently, depending on the wavelength of the material (Table 8.6). For example, white paint absorbs 20% of the shortwave radiation from the sun and 80% of the longwave radiation from heated objects. Selective

TABLE 8.6
Absorptivities and Reflectivities of Some Colors

Category	Light	Medium	Dark	Black
Absorbtivity factor	0.5	0.5 < M < 0.7	0.7 < D < 0.9	B > 0.9
Colors	White	Dark red	Brown	Black
	Beige	Light green	Dark green	Vivid blue
	Cream	Orange		Dark blue
		Light red	Light blue	Dark brown

TABLE 8.7
Shortwave Absorptivity and Longwave Emissivity of Some Materials

Substance	Shortwave Absorptivity	Longwave Emissivity
White plaster	0.07	0.91
Aluminum oil paint	0.45	0.9
Red bricks	0.55	0.92
Concrete	0.6	0.88
Gray paint	0.75	0.95
Black gloss paint	0.9	0.9
Perfect black body	1	1

surfaces are used in collector panels of solar collectors because they have high absorptivity for solar radiation but low emittance at ordinary temperatures. If we need to lose heat to the sky, we need the opposite effect in which a material will absorb less energy than it emits. Mediterranean lime-whitewashed architecture is a classical example of this effect, and white titanium oxide paints have these properties. Table 8.7 includes the absorptivity and emissivity of various materials.

When the material is not opaque and permits some flow of solar radiation, it has some degree of transparency, or transmittance. The visible transmittance (VT) is an optical property that indicates the amount of visible light transmitted. The VT is dimensionless in a scale from zero to one. Different types of glasses have different VT factors, depending on their surfaces, composition, or combination and in windows usually range between 0.3 and 0.8. A higher VT means that more light is transmitted (Figure 8.24). In general, glass is transparent to shortwave radiation but opaque to longwave radiation. Shortwave solar radiation from the sun is able to pass easily through a glass, heating objects inside the building, which then emit longwave radiation that cannot pass through the glass to the outside. This additional heat that is trapped inside the space, warming it, is called the greenhouse effect.

8.4.3 Effects of Solar Radiation

When the external hot surface of an element is exposed to solar radiation, its surface temperature can increase considerably, escalating heat flow by conduction to the interior or the building (because of the larger temperature difference). Solar radiation affects the surface temperature of the element and therefore heat flow by conduction. In warm climates, it is necessary to create shade, to use materials with low absorptivity, and to increase surface resistance with different surface treatments. In cold climates, it is necessary to promote solar gains and use dark colors. Of course, it is not feasible to change the color of a material as seasons change.

Total shortwave radiation (I_t), which reaches any surface on the earth, is the sum of direct solar radiation coming from the solid angle of the solar disc (I_d), diffuse celestial radiation (I_d), and the

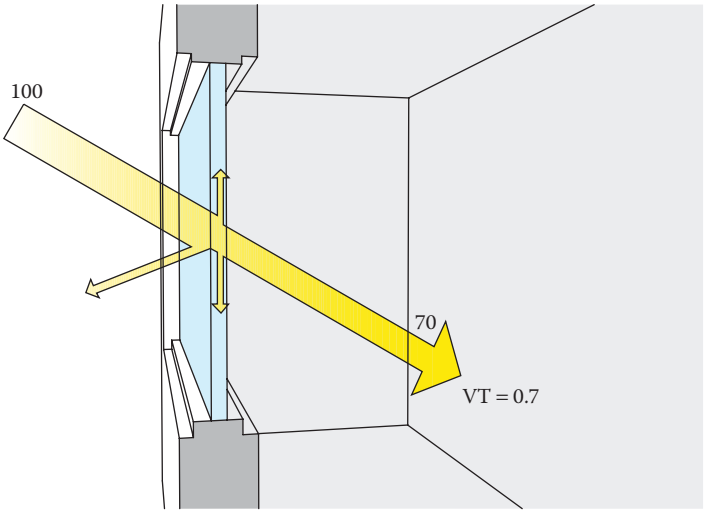


FIGURE 8.24 Transmittance through a transparent material.

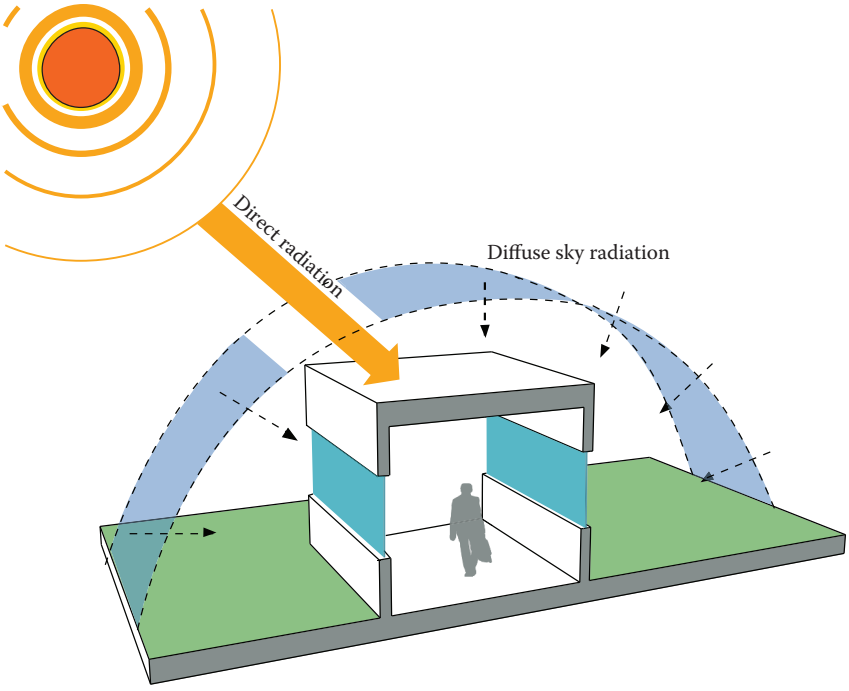


FIGURE 8.25 Diffuse and direct component of radiation received by a building.

reflected radiation of the adjacent surfaces (I_r) (Figures 8.25 and 8.26). The intensity of the direct component on a vertical surface is the product of the normal direct irradiation (I_{DV}) and the cosine of the incident angle (f) divided by the incident radiation and the normal to the surface.

$$I_t = I_{dr} + I_d + I_r \tag{8.18}$$

$$I_{DV} = I_{DN} \times \cos f \tag{8.19}$$

$$I_{TV} = I_{DN} \times \cos f + I_d + I_r \tag{8.20}$$

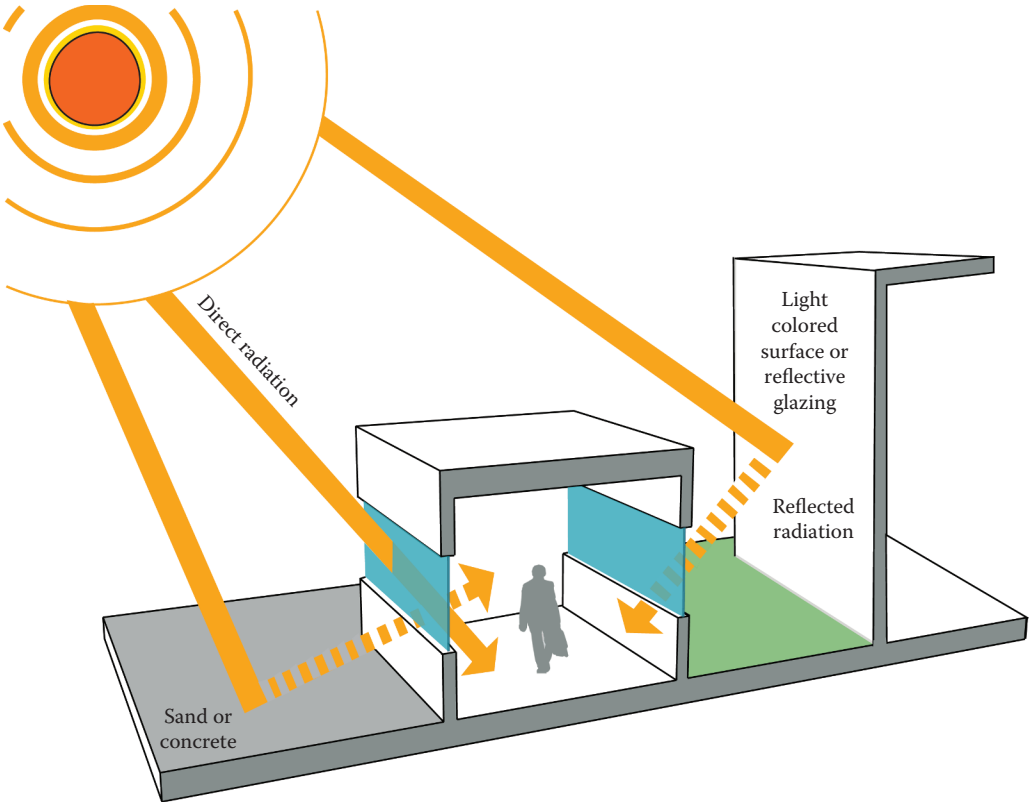


FIGURE 8.26 Radiation can be reflected to the building from surrounding areas.

Heat can be gained or lost by conduction through the envelope; however, in a warm climate solar gains are by far the most important source of heat gains in a building and in a cold climate can be the only source of external gains. In a warm climate it is necessary to minimize the amount of solar radiation falling on a building envelope. Any solar radiation will be absorbed by the building components, which will be heated and thus will increase conductive gains to the interior or heating the building directly by radiation through the windows. In a cold climate, solar radiation incident on the walls and through the windows will be beneficial because it adds heat to the building, potentially outweighing the losses by conduction due to the temperature differences between the interior and the exterior of the building. Heat gains through the windows are discussed in Chapter 7 on passive heating. The effect of solar radiation is different through the opaque and transparent elements of the building skin.

8.4.4 Opaque Components

The total solar radiation (I_t) incident on the building's walls or roofs is the sum of the direct, diffuse, and reflected components. After it hits the opaque components, part of the incident solar energy is reflected and another part is absorbed by the wall. The exterior side of the enclosure increases its temperature to a level higher than air temperature; part of the energy absorbed is dissipated to the exterior by convection and longwave radiation, and another part is transferred toward the interior by conduction through the wall or roof.

The effect of this heating by solar radiation on external surfaces is measured by the sol–air temperature, which combines the heating effect of the incident radiation falling upon a building with the effect of the hot air in contact with this surface. The sol–air temperature is the new surface

temperature used to calculate heat flow by conduction, accounting for the thermal effect of the incident solar radiation.

$$T_{SA} = T_o + \frac{a \times I_t}{h_o} = LWR \tag{8.21}$$

If

$$R_{Se} = \frac{I}{h_o} \tag{8.22}$$

$$T_{SA} = T_o + a \times I_t \times R_{Se} - LWR \tag{8.23}$$

where:

T_{SA} is the sol–air temperature (°C)
T_o is the outdoor air temperature (°C)
a is the absorptivity of external surface (%)
I is the intensity of solar radiation on the surface (W/m^2)
R_{Se} is the outdoor wall surface resistance coefficient (m^2 °C/W)
h_o is the overall external surface coefficient (radiant and convective) from the exterior surface to the environment. For design purposes, 20 W/m^2 °C with a wind speed of 3.5 m/s can be used.
LWR is the correction value resulting from the difference between environmental temperature and the temperature of the sky, due to radiant losses from the surfaces of the building. It results in a drop in temperature due to longwave radiation losses to the sky. For the roof it is about 6°C in a hot and dry climate with a clear sky, 4°C in a hot and humid climate with a clear sky, and about 0°C under cloudy skies. The value for vertical surfaces is negligible because these usually face surfaces with similar temperatures.

Applying this equation makes it clear that in the presence of solar radiation, materials with higher absorptivities will have a higher surface temperature than materials with lower absorptivities and more heat will be transferred to the interior. If a material is shaded from solar radiation, then its temperature will be equal to the temperature of the air.

8.4.4.1 Use of Shading Devices

As shown in the previous section, solar radiation on external surfaces can increase surface temperatures and thus the heat flow toward the interior of the building. Shading, by providing opaque devices between the sun and the enclosures, can significantly reduce the heat flow to the interior. If the incident radiation (I) is equal or tends to zero, then ($I \times a \times R_{Se}$) will tend to zero too, and the external surface temperature will be close to the temperature of the air (Figure 8.27). The heat flow

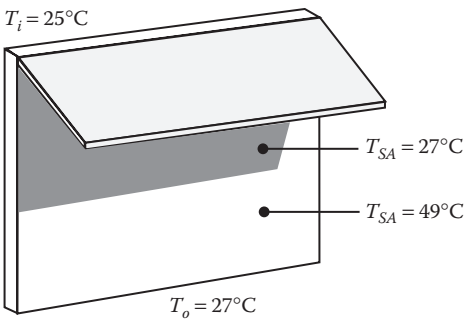


FIGURE 8.27 Solar protection for external walls.

in the interior of the building (Q) will then be lower than that of a similar portion of the facade that is exposed to the sun.

The conductive heat flow through an opaque element receiving solar radiation in its external face can be expressed as follows:

$$Q = U \times A \times [(T_{SA} = T_o + a \times \frac{I}{h_o} - LWR) - T_i] \tag{8.24}$$

or

$$Q = U \times A \times (T_{SA} - T_i) \tag{8.25}$$

where:

Q is the conductive heat flux (W)
U is the thermal transmittance (W/°C m^2)
A is the area of the wall (m^2)
T_i is the indoor temperature

8.4.4.2 Types of Solar Protection

Solar protection is usually classified as horizontal or vertical; however, in this case we will use the convention proposed by La Roche, Quirós, Bravo, Machado and Gonzalez (2001) in which the elements are classified according to how they are placed in relation to the building component. They can be placed parallel to the façade or perpendicular to the façade. Thus, a component that is perpendicular to a flat roof will be vertical, whereas a component that is parallel to a flat roof will be horizontal. These elements can be designed using the concepts of solar geometry explained in previous chapters.

8.4.4.2.1 Parallel Shading Devices

The direct solar component can be blocked with opaque components parallel to the building surface, with an external air circulation space. This system is used mostly in roofs or in east and west façades that require extensive solar protection. It has the disadvantage that it blocks all views from the building component toward the outside, and when used in roofs also blocks solar radiation flows toward the night sky. The energy flow through the opaque component and toward the enclosure can be described as follows:

1. The external face of the sunshade absorbs part of the solar radiation and the rest is reflected.
2. Absorption of the flow dissipates to the exterior by convection and longwave radiation. Another portion dissipates by conduction toward the interior surface of the sunshade.
3. A portion of the heat flowing through the sunshade dissipates in the air space by convection, and another portion flows toward the external surface of the wall or roof by longwave radiation.
4. Part of the flux absorbed by the external face of the wall or roof dissipates in the air space by convection. Another part is absorbed by conduction to the internal face of the enclosure.

A solar protection for a roof made of prefabricated panels (i.e., concrete, clay ceiling fillings) or galvanized iron sheets or fiber cement blocks incident direct solar radiation but does not allow radiation to escape toward the night sky (Figure 8.28). If the shading system can pivot, then it can be rotated so that it opens at night and the building components lose radiation toward the night sky (Figure 8.29). The Spanish *toldo* is an example of a movable shade that can be opened at night.

An alternate method is using a trellis covered with vines. Evaporation from the surface of the leaves will reduce their temperature below daytime air temperature (Figure 8.30). A green roof provides a similar effect, depending on the type of the vegetation planted on it.

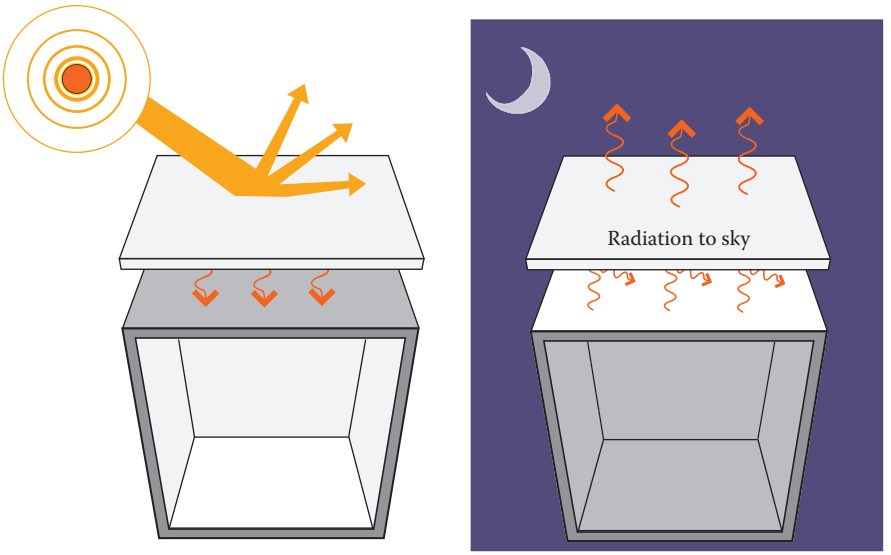


FIGURE 8.28 Shading of a roof with a parallel solar protection system.

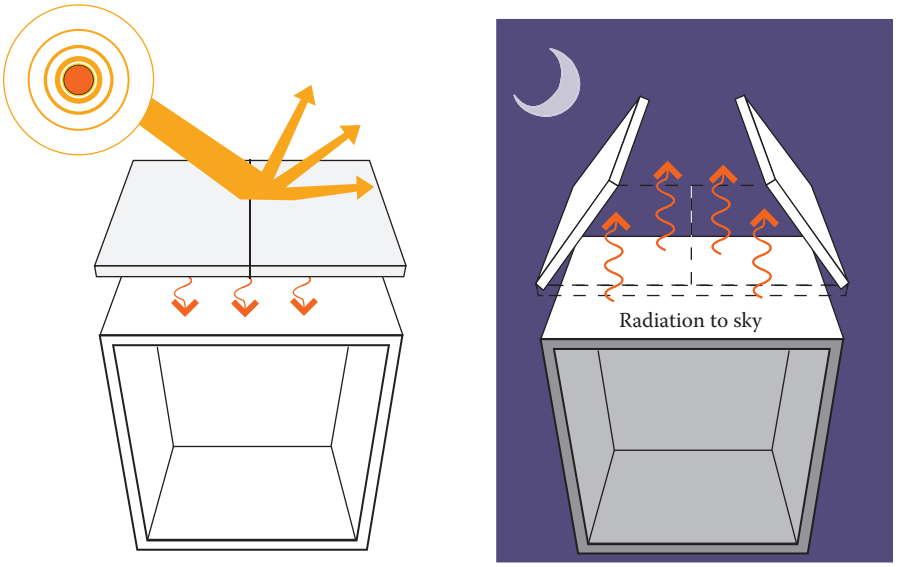


FIGURE 8.29 Operable parallel shade.

8.4.4.2.2 Perpendicular Solar Protection

Perpendicular solar protection systems are mostly used in walls and can be horizontal or vertical. In mid latitudes, horizontal systems are usually recommended for equatorial-facing elevations, vertical components for polar-facing orientations, and combinations of these for east- and west-facing orientations.

In addition to blocking direct solar gains, solar protection systems perpendicular to opaque enclosures provide some heat dispersion with fins. However, if they are connected to the internal structure, they can also create thermal bridges. Parallel solar protection can also provide some heat exchange through convective processes by pressure differences generated in the surface of the envelope due to small temperature variations.

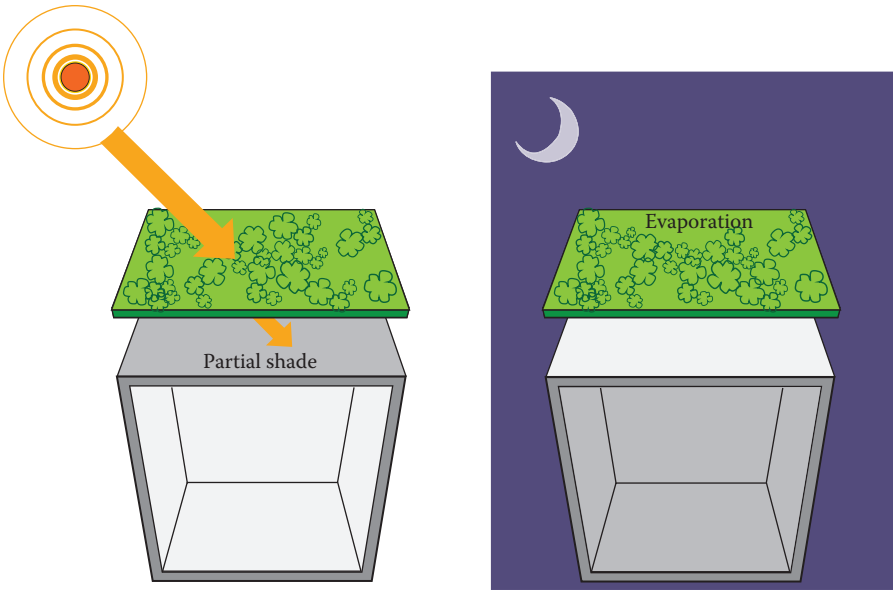


FIGURE 8.30 Parallel shading with vegetation.

8.4.4.3 Building Volume

The building volume can be conceived to maximize shading when necessary in the cooling season or to maximize solar gains when necessary in the heating season. Buildings can be designed as convex or concave configurations, which, depending on latitude, azimuth, and angle, will either block or receive solar radiation. There is an opportunity here to generate algorithms or generative design systems that provide optimum building skin configurations for different types of climates. A tool in this direction was developed by da Veiga and La Roche (2003). This tool evaluated solar radiation on building envelopes using Maya, a three-dimensional (3D) modeling and animation software, and analyzed the surfaces of complex envelopes with different orientations using the potential amount of solar radiation that each surface section received as a function of the angle of each one with the sun (Figure 8.31). The different surfaces could be analyzed for a particular day and latitude and a specific outdoor average temperature. A fitness function determined and rated the individual and overall performance of the proposed building envelope. This tool worked as a rating system for complex architectural forms to aid in the evaluation of complex building envelopes as a function of incident energy, allowing the performance of each proposed envelope to be determined. The tool was not developed further, but now several tools such as Ecotect incorporate this function, permitting the user to determine optimum orientations for solar hot water collectors, photovoltaic panels, or windows to collect solar gains to the interior of the building.

8.4.4.4 Opaque Surface Finish

Roughness is related to the texture of the building's enclosure surfaces on a small scale. Grades of roughness are established according to the size of the grain, expressed in millimeters. Larger or smaller roughness on the exterior skin of the building has little effect on temperature. However, a very bumpy skin favors radiant exchange between the radiant surface and the sky, but can also reduce connective exchanges.

Highly textured walls have one part of their surface in the shade. The absorption area of the textured surface is smaller than its emission area and will thus be cooler than a flat surface. The enlarged area can also generate an increase in the heat convective transfer coefficient, which will

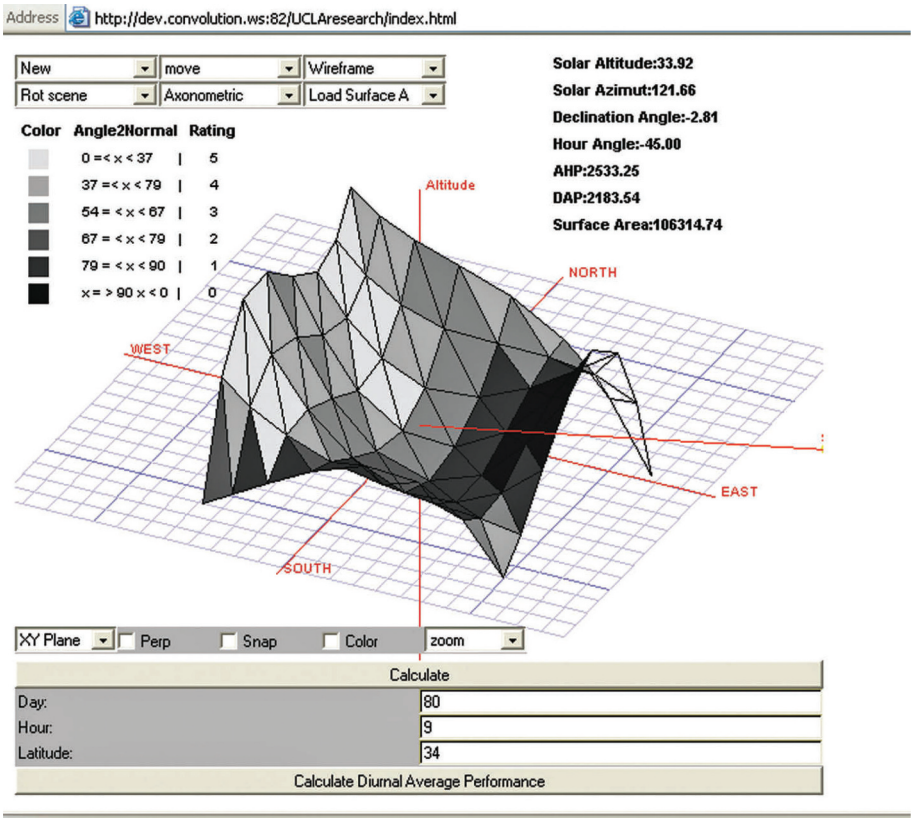


FIGURE 8.31 A computer tool for the analysis of direct solar radiation in complex architectural envelopes: EvSurf.

allow faster cooling of the building during nighttime when the surrounding temperature is lower than the temperature of the building.

8.4.4.5 Selection of Absorptive, Reflective, and Emissive Materials for Exterior Surfaces

These concepts were discussed earlier in the chapter. If absorptivity decreases, then the outdoor temperature will be closer to that of the air temperature, and the heat flow toward the interior of the building (Q) in the summer will be lower. The external surface color has a significant effect on the impact of the sun upon the building and the temperature in the interior spaces. Materials with darker colors, such as black, are the most absorptive, whereas light colors are the least absorptive. Radiation delivered by a material from its surface is equal to absorption when it is at identical wavelength. But the solar radiation absorbed by a surface is not necessarily equal to the radiation emitted, because the temperature of this material is much lower than that of the sun.

Some cold materials absorb a reduced proportion of solar radiation but deliver radiation freely. They maintain relatively low temperatures even when exposed to the sun. Other materials absorb a high proportion of solar radiation but have reduced emissivity. These surfaces maintain high temperatures and reduced heat losses. Figure 8.32 shows a selection of materials with different combinations of absorptivities and emissivities that can be used for different purposes.

8.4.4.6 Building Components That Are Transparent to Solar Radiation

Transparent and translucent building components such as windows or skylights have several functions in any climate; they provide daylight, visual contact with the outside, solar gains in the winter,

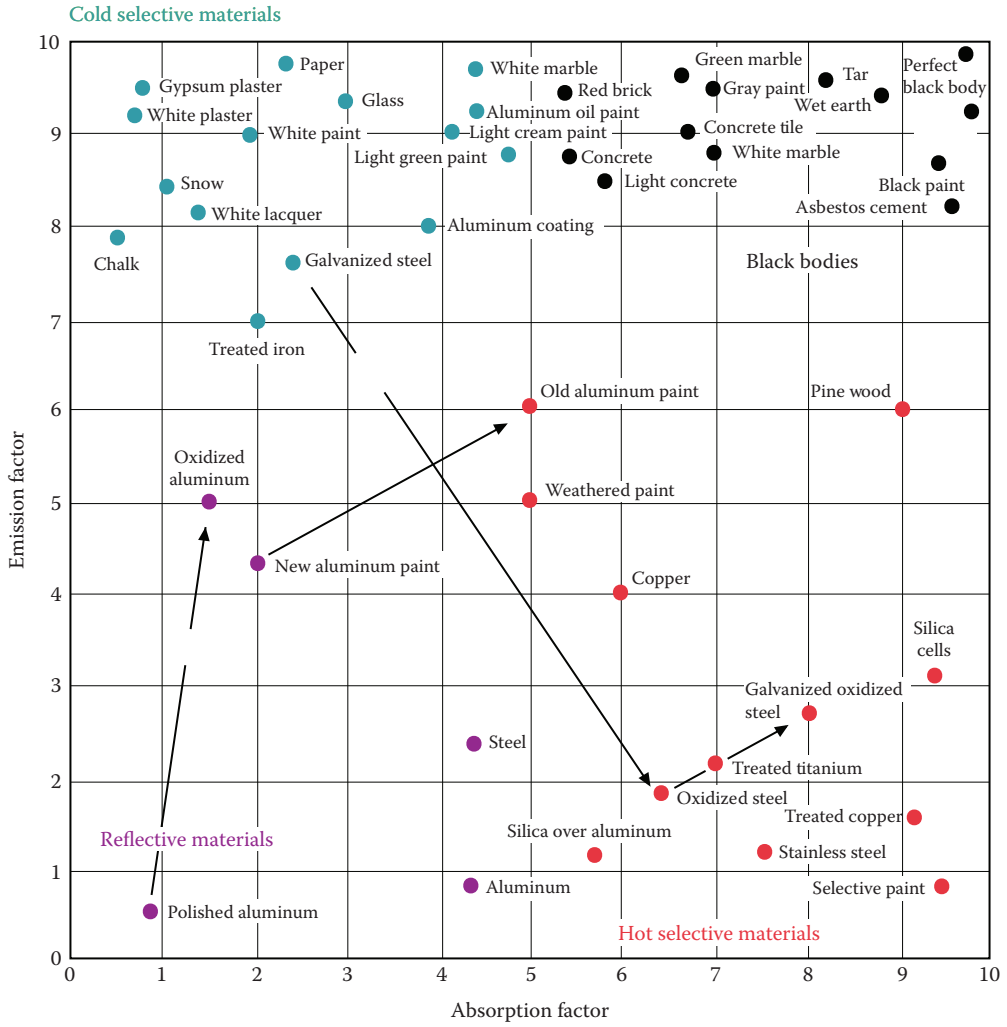


FIGURE 8.32 Emissivity and absorptivity of some materials.

and ventilation in the summer. Windows are major contributors of heat by transmission of radiation and reradiation toward the interior of the space. This is beneficial in the winter but not in the summer. Glass is also responsible for the greenhouse effect, which is important to consider when calculating thermal gains through windows. In addition to heat gains by radiation, a window can provide gains or losses by conduction and ventilation.

The following equation is used to determine the heat flow through a glazed opening:

$$Q = A \times I \times f \tag{8.26}$$

where:

A is the window area in m^2

I is the solar radiation intensity on the window surface in W/m^2

f is the window glass solar gain factor, which depends on the type of glass and incidence angle, measured from the normal to the surface. It is expressed as a decimal fraction of the incident radiation that reaches the interior and in the United States it is called the solar heat gain coefficient (SHGC).

The value of *f* varies as a function of the geometrical relationship between the window and the solar radiation, which is a function of the latitude, time of day, and orientation and angle of the component. This radiation has three components: direct, beam, and diffuse. The sum of them is the total radiation upon the surface.

8.4.4.7 Appropriate Window Selection to Control Solar Radiation

Of the radiation that hits the window, part of it is absorbed, part of it is reflected, and part of it is transmitted toward the interior of the space. Because heat gains through windows and skylights can be an important part of the thermal gains in a building, it is important to select appropriate window types for each climate and orientation.

Because of the need to control this solar radiation, the glazing itself becomes an important mediator between the building and the exterior. Until around the 1950s, most architectural glazing was clear, transmitting 80%–90% of visible and total solar radiation, and consisted of a single layer of glass. Now, many types of higher performance glazing systems regulate energy (heat and light) in different ways.

In a clear single-pane window, most of the solar radiation is transmitted toward the interior of the space (Figure 8.33). In a heat-absorbing tinted glass, a large portion is absorbed, of which most is reradiated toward the interior of the space (Figure 8.34). In a reflective glass, a larger portion is reflected toward the exterior (Figure 8.35). Of course, these numbers are approximations and vary depending on the manufacturer and specific windows.

The SHGC measures how well a window blocks heat from sunlight and indicates the percentage of solar radiation incident upon a glazed aperture that ends up as heat inside the space. The SHGC does not have a dimension; the maximum theoretical resistance is zero, and the minimum one is calculated based on the performance of the whole glazing unit, measured using the rough opening and not just the glass portion. In reality it ranges from around 0.2 to 0.9 because no window completely blocks the heat or allows all the flow of heat inside the space. The SHGC is affected by the type of glass, number of panes, tinting, reflective coatings, and shading by the window or skylight frame.

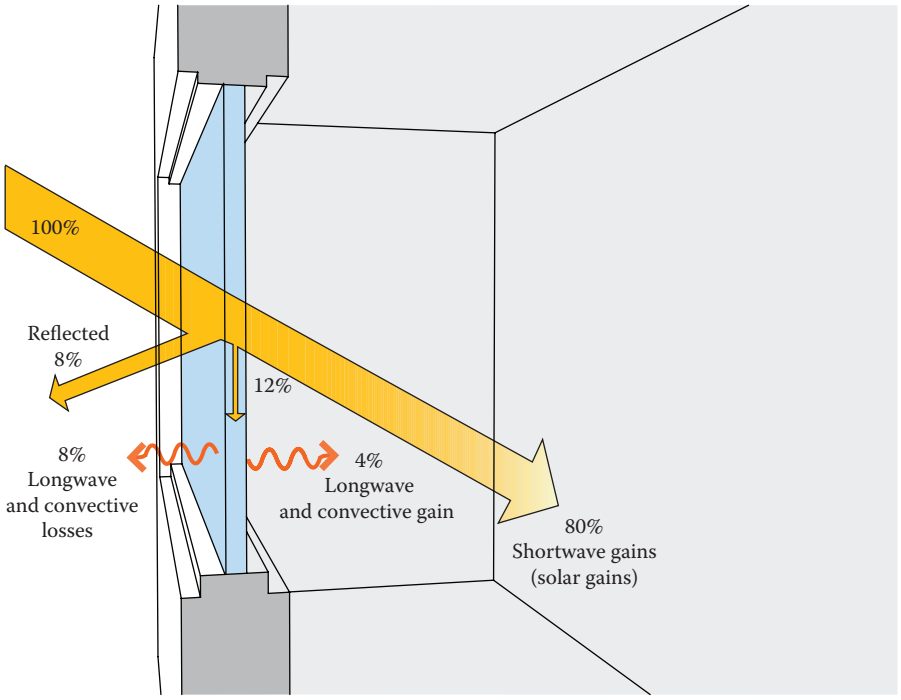


FIGURE 8.33 Solar energy balance in a single-pane window.

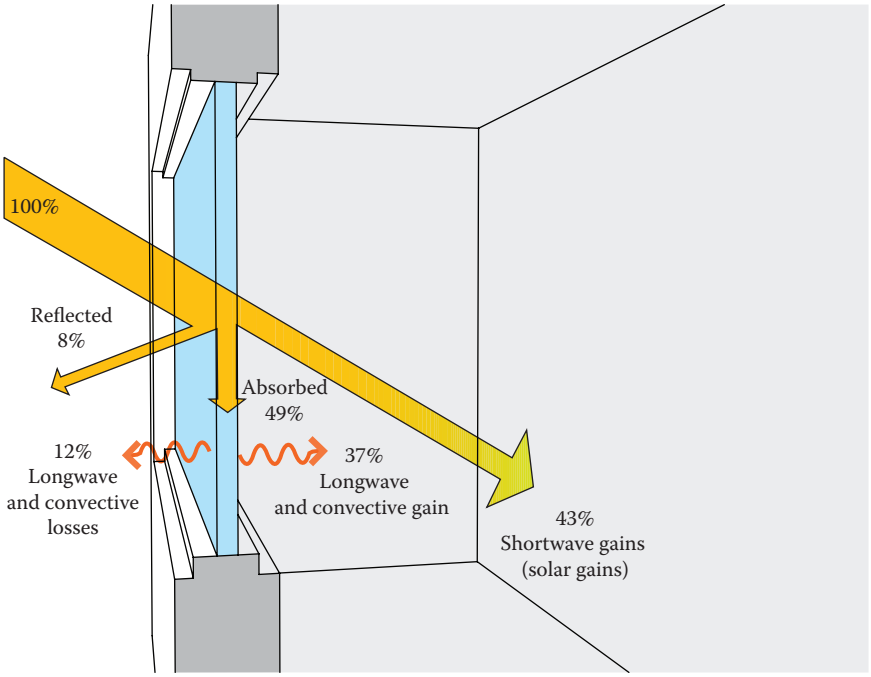


FIGURE 8.34 Solar energy balance through heat-absorbing tinted glass.

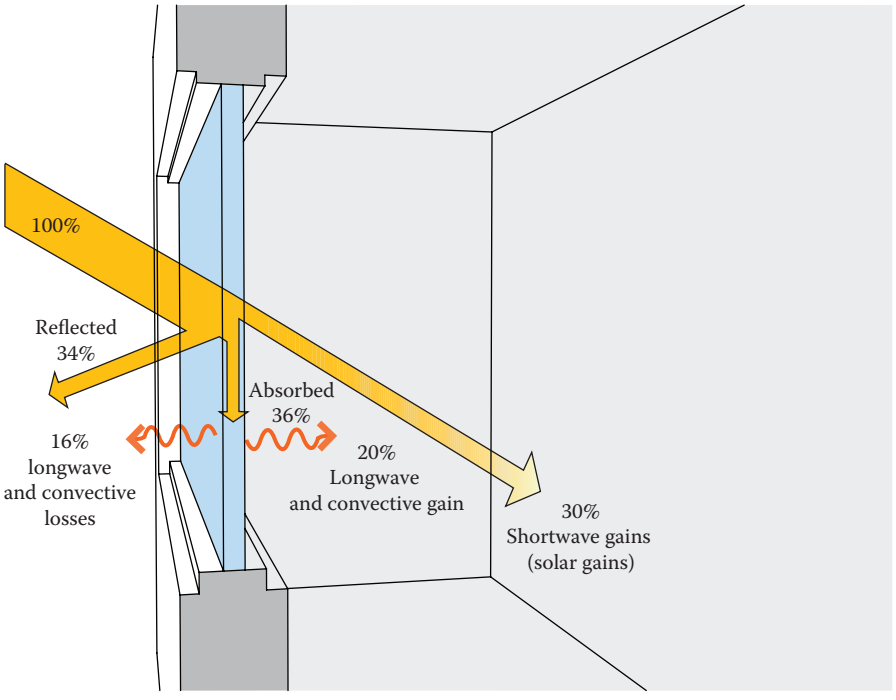
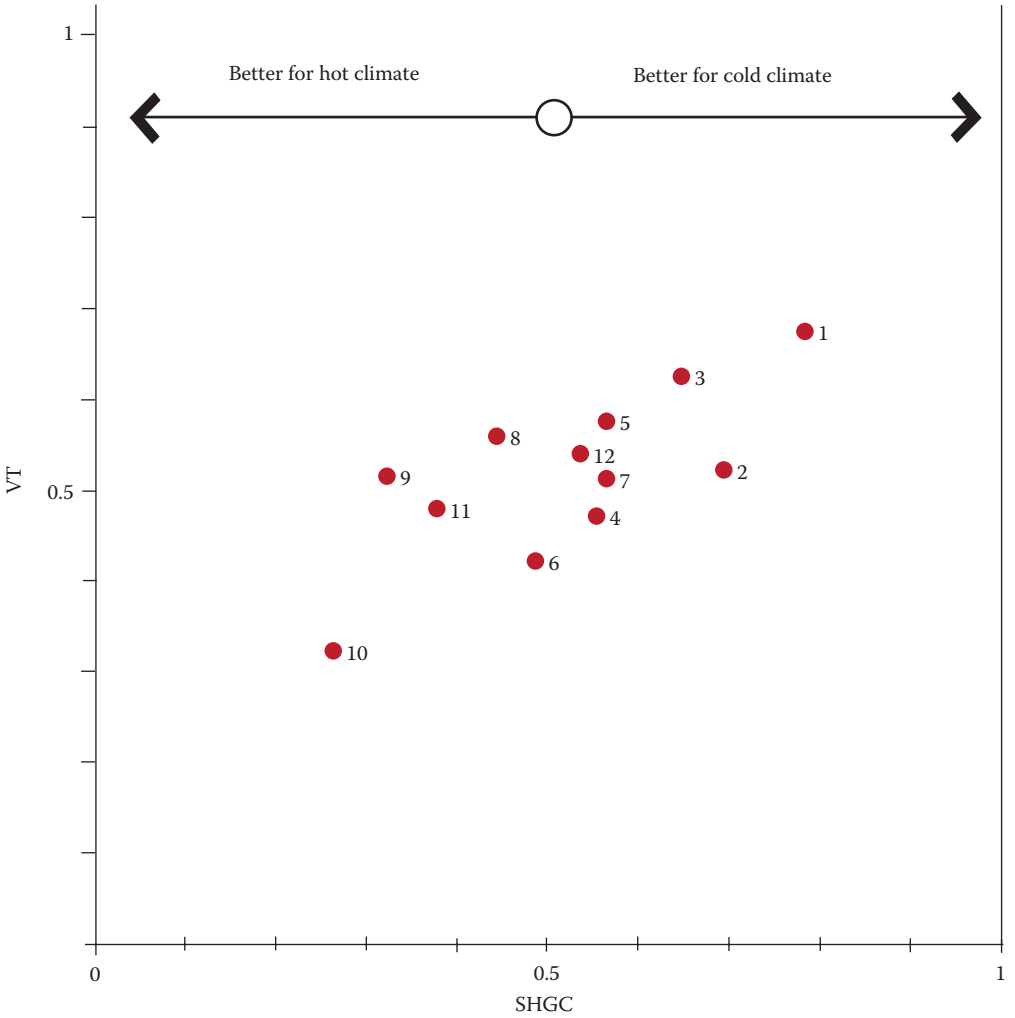


FIGURE 8.35 Solar energy balance in a window with reflective glass.

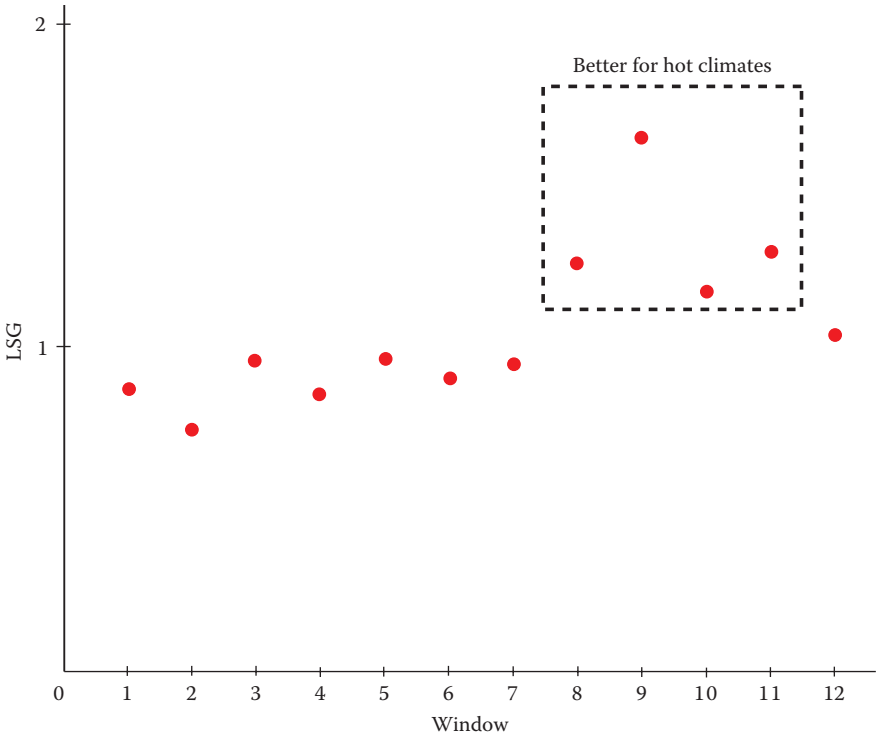
In general, if solar gains are required it is preferable to have a high SHGC (allows more heat), and in cooling climates it is preferable to have a low SHGC (blocks more heat). Summer gains can be controlled by shading devices.

The SHGC quantifies the total amount of the solar radiation spectrum penetrating through the window, whereas the VT quantifies only the visible portion of the spectrum. The relationship between the SHGC and the VT is expressed as the light-to-solar-gain ratio (LSG) obtained by dividing the VT by the SHGC. All windows should provide daylighting. However, windows in hot climates should have a low SHGC because any solar gain through window increases cooling load, whereas windows in cold climates should have a higher SHGC because any gain through windows could reduce heating loads (Figures 8.36 and 8.37). They should all be good insulators and should



1. Single-glazed clear aluminum no thermal break
2. Single-glazed bronze aluminum no thermal break
3. Double-glazed clear aluminum thermal break
4. Double-glazed bronze aluminum thermal break
5. Double-glazed clear wood or vinyl
6. Double-glazed bronze wood or vinyl
7. Double-glazed low-e wood or vinyl
8. Double-glazed low-e wood or vinyl
9. Double-glazed spectrally selective wood or vinyl
10. Double-glazed spectrally selective wood or vinyl
11. Tripled-glazed low e superwindow
12. Triple-glazed clear

FIGURE 8.36 Visible transmittance and solar heat gain coefficient in different window types.



1. Single-glazed clear aluminum no thermal break
2. Single-glazed bronze aluminum no thermal break
3. Double-glazed clear aluminum thermal break
4. Double-glazed bronze aluminum thermal break
5. Double-glazed clear wood or vinyl
6. Double-glazed bronze wood or vinyl
7. Double-glazed low-e wood or vinyl
8. Double-glazed low-e wood or vinyl
9. Double-glazed spectrally selective wood or vinyl
10. Double-glazed spectrally selective wood or vinyl
11. Tripled-glazed low-e superwindow
12. Triple-glazed clear

FIGURE 8.37 Control of solar radiation LSG.

be airtight to reduce infiltration when they are closed. These two factors become more important as the difference between the indoor and the outdoor temperature increases.

Low-emittance coatings (low-E) are applied to one of the glass surfaces facing the air gap between the layers of glazing. They are microscopically thin, almost invisible metal or metallic oxide layers deposited on a window or skylight glazing surface. The principal mechanism of heat transfer in multilayer glazing is thermal radiation from a warm pane of glass to a cooler pane. A low-E coating blocks a large portion of the heat transfer by radiation through the glazing panes and increases the overall resistance of the window (lower overall *U*-value). Low-E coatings are transparent to visible light but reduce ultraviolet (UV) transmission through the window. Different types of low-E coatings have been designed to allow high solar gain, moderate solar gain, or low solar gain. Higher solar gain windows perform better in the winter, and lower solar-gain windows perform better in the summer. In cooling-dominated climates, windows with lower solar gain are better because all heat entering the building contributes to increase the heat gain. Depending on the position of the coating, the windows will block the heat entering or leaving the space. These windows must then be selected accordingly for summer or winter use. They must block heat gains in the summer and heat losses in the winter while providing the possibility for gains in the winter.

Several types of photosensitive or photochromatic glass have been recently developed to turn dark when exposed to intense light and to recover their transparency when the luminous source

disappears. The transmittance of these windows can vary by about 30% at a time and between 74% and 1%, for example, 1%–20%, 15%–40%, 35%–55%, and 50%–75%.

Windows with *U*-values below 1.5 W/m^{2}K can be constructed in several ways. Most of them are double- and triple-glazed systems that use coatings with low emissivity and noble gases between the glazing layers. Double-glazed units with low-E coating and argon can be built with values about 1.3 W/m^{2}K, and can achieve up to 0.56 W/m^{2}K. The problem with many of these gas-filled glazing systems is that they lose most of the gas over time.

New windows use silica aerogel, which is transparent to visible solar radiation but is very insulating with a very low thermal conductivity around 0.021 W/m^{2}K, greater than that of still air (0.026 W/m^{2}K). Some of these have been built inside evacuated aerogel glazing constructed as a sandwich by inserting a 20-mm-thick aerogel disk between the two glass panes with *U*-values around 0.5 W/m^{2}K. Manufacturers such as Kalwall now make systems using Nanogel® in a translucent aerogel that provide *U*-values from 0.45 to 0.85 W/m²K (0.08 to 0.15 Btu/(hr/ft²/°F) and even superinsulating systems with *U*-values of 0.30 W/m²K with 20% light transmission (for R-20 *U*-value of 0.05 Btu/(hr/ft²/°F). These glazing systems reduce heat losses and gains by conduction while still permitting daylight inside the space.

8.4.4.8 Orientation of Buildings and Openings

In addition to selecting the appropriate window for each climate and orientation, other strategies can be implemented to reduce the amount of solar radiation that is reaching each transparent component.

The orientation of the windows (and the building) has an important influence on the energy flows, which is also affected by the magnitude of the maximum radiation, the time of day when maximum radiation occurs, the number of hours the surface receives solar radiation, and the ground albedo.

It is usually better to orient buildings with the longest elevations facing toward the north and the south. The equatorial-facing elevation will usually receive more solar radiation in the winter, whereas the polar-facing elevation will receive more solar radiation in the summer, which is not beneficial if cooling is necessary. However, east and west should usually be smaller because even if solar radiation is beneficial in these elevations in the winter it is not helpful in the summer when the sun is more intense during the morning and the afternoon because it is more perpendicular to the façades. These are general rules, though, and the only way to determine the optimum orientation of a project in a specific location is with energy modeling software that uses local temperature and solar radiation data to predict energy use or thermal comfort.

In intertropical latitudes, where seasons are not very differentiated and where the sun reaches high altitudes, choosing between south and north is not significant. It is important to avoid east and west orientations that are lit by the sun's rays in the morning and in the afternoon with incidence near to the normal of the façades and thus are more difficult to protect. In these latitudes, it is the roof that becomes a critical building component, because the sun is high in the sky during most of the year with an angle of incidence closer to the normal with the roof.

Skylights in the roofs also affect thermal gains. Horizontal toplights allow abundant solar radiation during the whole year in lower latitudes and during the summer in mid latitudes, increasing cooling requirements. Equatorial-facing clerestories are usually better in mid latitudes because they can be easily shaded to permit solar radiation in the winter but block solar radiation in the summer when the sun is higher up in the sky.

Eolic orientation can be very important in some cases, such as coastal and tropical zones with very predictable wind patterns or frequent and intense winds. However, air movement is very unpredictable and can be easily affected by local obstacles. Solar orientation is usually more predictable and more important than eolic orientation.

8.4.4.9 Glazing-to-Surface Ratio

The dimension of the glazed surfaces affects the amount of total solar energy (diffuse, direct, and global) that can penetrate the building. Larger glazed areas increase the potential for gain

and for losses by conduction, affecting the interior air temperature, especially during daytime. More energy inside the building leads to higher temperatures, which in turn leads to a larger indoor temperature swing. The glazing-to-surface ratio is usually calculated by dividing the amount of glazing in the elevations by the surface area (e.g., walls or floor). This ratio can also be calculated as a function of different orientations, for example, as a function of the equatorial-facing glazing-to-floor ratio. The effect of this ratio is discussed in more detail in the section on passive heating.

8.4.4.10 Use of Shading Devices

Because solar radiation can greatly impact internal temperatures and can be blocked easily, shading systems are extremely important to control heat gains by radiation through the windows. The types of shading devices and the process to design them have been explained in detail in Chapter 5. Solar protection systems can be fixed or operable and internal or external. Fixed systems are rigidly attached to the building without possibility of regulation. Operable systems allow more flexibility because they can be adjusted manually or automatically, but they require more maintenance.

External shading devices in the form of simple opaque devices between the sun and the openings will reduce the amount of solar radiation on the window and inside the building. Interior shading devices such as blinds and interior curtains are not very efficient, because they block solar radiation after it has already entered the space. The radiation blocked by the blinds or curtains is absorbed by them, heating them and also heating the space by convection and radiation. Half of this reirradiation is toward the inside, and half is toward the outside. Because it is longwave, though, the glass of the window blocks it, and this radiation stays inside. The space between the blind and the window is overheated, and the heat of the blind itself increases the MRT above the air temperature. There are many ways to improve the performance of the window by blocking solar radiation and increasing insulation levels, and some are shown in Figure 8.38.

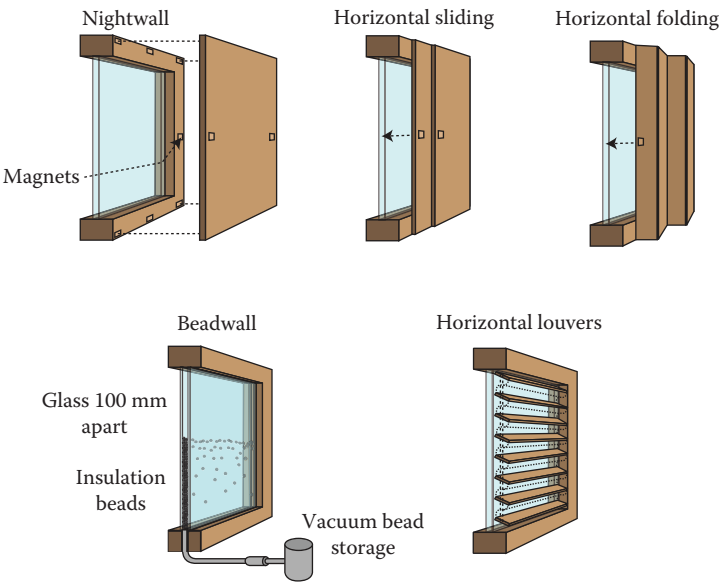


FIGURE 8.38 Different types of movable insulation. (Based on illustrations in Lewis, O. 2001. *A Green Vitruvius: Principles and Practice of Sustainable Architectural Design*, 2nd ed., James and James, London, 2001.)

8.5 HEAT TRANSFER BY CONVECTION

It is important to understand that ventilation can be used for three completely different processes in a building; depending on this process, this exchange of air can be labeled differently. It can be used to supply fresh air, to remove internal heat, and to promote heat dissipation from the body. It can also be deliberate or incidental, which is usually called infiltration. In this section, only the exchange of heat between the interior of the space and the exterior is discussed.

8.5.1 Definition

Convection is the process of heat transfer by flowing and mixing motions in fluids. It is primarily dependent on air temperature. Natural convection occurs when molecules of cool air absorb heat from a warm surface, rise, and carry it away. As a gas or liquid acquires heat by convection, the fluid expands and becomes less dense, rising on top of the denser and cooler fluid. The resulting currents transfer heat by natural convection. The effect of convection on people is reduced by the amount of clothing people are wearing. Layered air spaces in building materials also act as insulation. Heat flow by convection requires a fluid to be present (air), is directional, never convects down (unless it is forced), requires a temperature change, can be blocked completely by obstacles, and is affected by gravity.

Natural convection can be produced in several ways. If there is an air space enclosed by two horizontal elements and the upper element is cold and the lower element is warm, then the air will flow upward and then will descend as it loses its heat in the ceiling (Figure 8.39). However, if there are two horizontal elements and the upper element is warm and the lower element is cold, then the warm air will stay in the upper portion of the space because it is less dense than the cooler air below. Heat will still be transferred from the upper portion to the bottom portion by radiation.

If there are two opposing walls and one is warm and the other wall is cold, then the air flows from the warm wall upward and descends down the colder wall, losing its heat. This process can occur in wall cavities when the air gap between the components is large enough (Figure 8.40).

Forced convection occurs when the air is moved by a fan or by the wind and is circulated in a direction in which it would not naturally go.

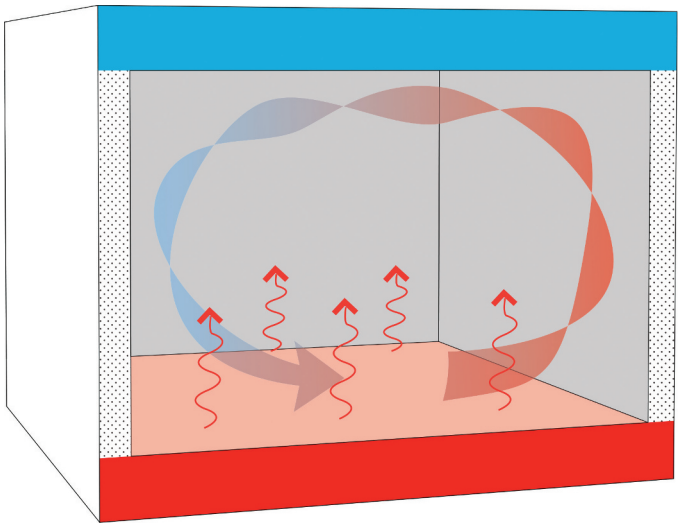


FIGURE 8.39 Natural convection.

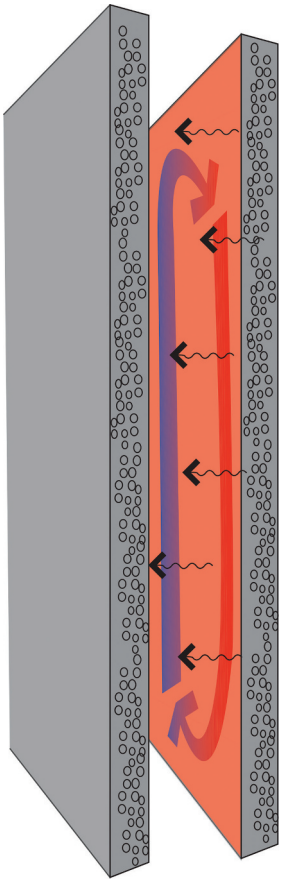


FIGURE 8.40 Convection between vertical elements in a wall.

8.5.2 Air Movement and Infiltration

Heat transfer by convective effects occurs when there is a temperature difference between the internal and external environments of a building (indoor and outdoor). The environment with the highest temperature has more energy and transfers this energy to the area with the lower temperature by ventilation (natural or forced) and infiltration. The amount of heat transferred increases as the temperature difference increases or the air exchange rate increases. The amount of sensible heat transferred is a function of the difference in temperature, the airflow rate, and the volumetric mass of air and can be calculated using

$$Q_v = \rho \times C_p \times v \times \Delta t \tag{8.27}$$

also expressed as

$$Q_v = 1.2 \times v \times \Delta t \tag{8.28}$$

where:

Q_v is the amount of sensible heat transferred (W)
ρ is the density of air (kg/m^3)
C_p is the air-specific heat (J/kg K)
The product $\rho \times C_p = 1.2$ kg/m^3 × 1,000 kJ/kg K = 1,200 J/kg m^3 in locations below 500 m above sea level.

v is the air flow rate (m^3/s)
Δt is the temperature difference between outside and inside ($T_o - T_i$)
T_o is the outdoor air temperature (K)
T_i is the building's internal air temperature (K)

In the United States with the IP system, this is usually expressed as

$$Q_v = 1.1 \times v \times \Delta t \tag{8.29}$$

where:
Q_v is the sensible heat flow rate by infiltration or ventilation (Btu/hr)
1.1 is the constant derived from the density of air at 0.075 lb/ft^3 multiplied by the specific heat of air and by 60 min/hr (min/ft^3 hr °F)
v is the outdoor airflow rate in cubic feet per minute (cfm)
Δt is the temperature difference between the outdoor air and the indoor air ($T_o - T_i$) (°F)

It can also be measured in cubic feet per hours, in which case

$$Q_v = 0.018 \times \mathrm{CFH} \times \Delta t \tag{8.30}$$

where:
Q_i is the heat flow rate by infiltration
CFH is the cubic feet per hour of air infiltrated in the space and can be determined using different methods
Δt is the temperature difference between the indoor and the outdoors ($T_o - T_i$)

The airflow rate is estimated with

$$v_r = N \times \frac{V}{3{,}600} \tag{8.31}$$

where:
N is the number of air changes per hour (ac/hr)
V is the volume of internal space (m^3)

The relationship between the outside and inside temperatures will vary according to the daily temperature cycles and climatic, microclimatic, and seasonal variations. There will be moments in which the outside temperature is higher than the indoor temperature and moments in which the indoor temperature is higher. Outside air is a source of free heating and cooling that must be used whenever possible to reduce the strain on mechanical heating and cooling systems. During the cooling season, if the outdoor air is cooler than the indoor air, ventilation should be promoted. During the heating season, if outdoor air is warmer than indoor air, ventilation should be promoted. This is much less common, and ventilation is used much more to cool the building by eliminating warmer air. Ventilation as a passive cooling strategy is discussed in more detail in Chapter 9.

8.5.3 Controlling the Exchange of Air

Because ventilation can result in either heat gains or heat losses, it is important to control these exchanges according to requirements and needs. In general, if cooling is required, then the building should be

1. Closed when the outdoor temperature is higher than the indoor temperature
2. Open when the indoor temperature is higher than the outdoor temperature

These rules can change; for example, increasing the difference between the indoor and outdoor temperatures before ventilation occurs might be recommended. La Roche and Milne (2004) tested a smart ventilation system in several experimental test cells, and after evaluating several control strategies with different relationships between them, such as air change rates, values for comfort low and comfort high, and amounts of thermal mass, it was found that a higher air change rate during the cooling period increases the amount of heat that is flushed out of the building, lowering the temperature of the mass, and lowering the maximum temperature for the next day. The test cells that had the smart ventilation system, and could increase the air change rate when needed, always performed better than the test cells with a fixed infiltration rate. The system performed better with maximum air change rates of 15 air changes/hour rather than 4 air changes/hour, but satisfactory results were achieved with maximum air change rates of only 4 air changes/hour, probably because of the limited amount of mass inside the test cells. These results are discussed further in Chapter 9.

In hot climates, when cooling is required, there will probably still be some moments in which the outdoor air temperature is lower than the indoor air temperature ($T_i > T_o$). During these periods, the building will be losing energy to the outside, a process that can be accelerated by increasing the rate of exchange of air between the indoors and the outdoors. When the outdoor temperature is higher than the indoor temperature, there will be heat gain from the outside, and it is better to reduce heat transfer by convection to the minimum to maintain indoor air quality (IAQ). Thus, to avoid elevated indoor air temperatures, it is necessary to seal the building when the external temperature is higher than the internal temperature ($T_e > T_i$) or to open the building when the external temperature is lower than the internal temperature ($T_e < T_i$). In other words, it must be possible to seal and open the building as necessary depending on the indoor–outdoor relationship. This is usually achieved with windows or fans, which could be automatic or manual.

8.5.3.1 Seal the Building When $T_e > T_i$

When ventilation would cause heat transfer to the building's interior (heat gain), the building should be sealed (no exchange of air). However, even when it is sealed, a minimum supply of fresh air must still be available to eliminate indoor pollutants. Air movement can also be generated inside the building without the need to exchange air using portable or ceiling fans. Fans provide huge energy savings compared with mechanical cooling systems in nonextreme climatic situations. It might also be necessary to dehumidify indoor air to reduce the humidity generated by equipment and people. Kitchen and laundry areas can be kept separate from the rest of the building, and humidity can be extracted with forced ventilation. If air temperature and humidity levels increase beyond tolerable levels, then it is necessary to use mechanical cooling.

8.5.3.2 Open the Building When Outdoor Temperature Is Lower than Indoor Temperature ($T_o < T_i$)

This process dissipates hot air from inside the building by exchanging it with cooler outdoor air. There are two basic types of building ventilation that vary depending on the type of building (low mass versus high mass) and the type of climate (hot and humid versus hot and dry).

In hot and dry climates, it is important to maximize the air change rate to promote heat exchanges and cooling of the building structure during the night, when the outdoor temperature is lower. Cooling the thermal mass at night will provide a cool internal surface to absorb heat during the day, keeping it cool.

In warm and humid climates, it is important to maximize air speeds inside buildings to cool the occupants and to produce physiological cooling and more thermal comfort. An increase in air velocity promotes evaporative cooling of the skin and reduces thermal resistance of the air film around the human body. Air movement is helpful only when the outside air temperature is lower than the temperature of the skin (about 34°C).

In hot, humid climates, cross-ventilation is the most effective strategy to promote thermal comfort, both by evacuating the heat that can accumulate inside the building and by creating air velocities that can promote physiological cooling of the skin.

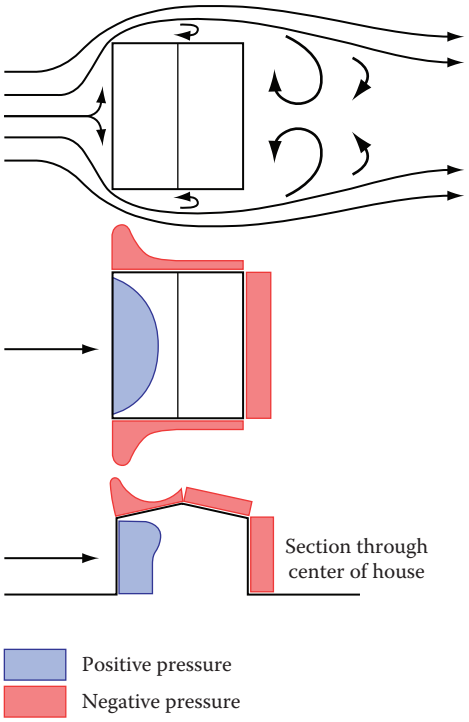


FIGURE 8.41 Distribution of the pressure fields around a building.

Ventilation takes place by naturally occurring pressure differences that generate an exchange of air between the exterior and the interior. These pressure differences can be caused by wind or by the buoyancy effect created by temperature differences.

When wind reaches the windward side of the building, it is blocked and a positive static pressure zone is created while a negative pressure zone is created at the opposite side of the building. If there are windows on both sides, the difference between the high pressure at the windward side (entry area) and the low pressure on the leeward side (suction zone) will generate a flow of air through the building (Figure 8.41).

In many cases, cross-ventilation can reduce the use of mechanical cooling. With air speeds of 0.57 m/s and 0.85 m/s, reductions in the perceived internal temperature between 2.2 and 2.7°C were attained (Cook, 1986). Other research suggests that a 1 m/s air velocity at the body surface creates a perceived cooling effect of 3 K and 1.5 m/s up to 5 K.

The factors that affect the quality of the design as it relates to the air movement inside the space are as follows:

The building envelope and the location and design of the internal elements and how they affect the internal air distribution
The shape of the building and ventilation induction to the inside
The elements surrounding the building (natural and architectural)

8.5.3.2.1 The Effect of the Skin and Internal Elements on Airflow

Different studies carried out on scale models in wind tunnels have evaluated the relationship among the space geometry, location, and shape of the openings on cross-ventilation, which must be considered during the design process to optimize ventilation. These studies have generated several well-known but useful principles:

There should be an inlet opening or window and an outlet or exit to maximize wind speed.
There must be a pressure difference between these two for air to flow through the space.
An outlet larger than the inlet allows more opportunities to direct the flow of air in different directions.
Different size windows for inlets and outlets affect the air velocity inside the space. Wind speed averages inside the space are higher when both openings are larger. If the inlet is larger than the outlet, the air velocity will increase close to the outlet (Venturi effect). However, this is not usually helpful. If the inlet is smaller, then air velocities will usually be higher close to it, creating more potential for air penetration. A larger difference between the inlet and outlet will generate higher air velocities. Sobin (1981) recommended a ratio of $A_o/A_i = 1.25$ for the highest indoor speed ratios, where A_o = area of outlet and A_i = area of inlet. Higher ratios will produce higher velocities close to the inlet but lower averages across the whole room.
The location of the outlet does not significantly affect the airflow pattern (Figure 8.42) and the location of the inlet affects the airflow pattern (Figure 8.43). Because the air has mass it has inertia and will continue flowing in the direction that it entered.

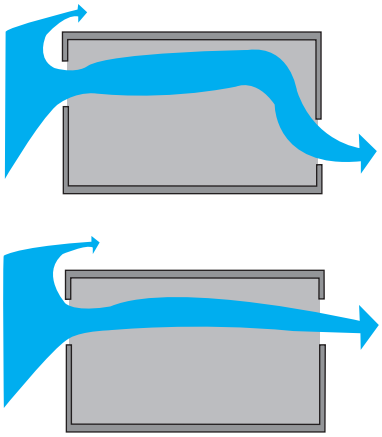


FIGURE 8.42 Location of the outlet affects only the direction of the airflow at the end.

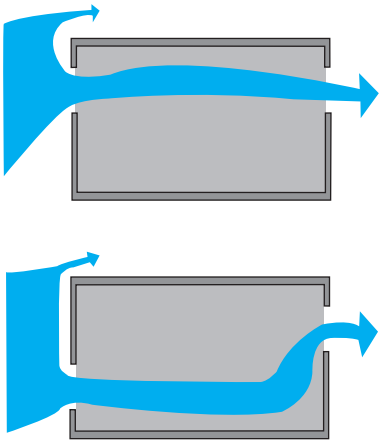


FIGURE 8.43 Location of the inlet affects airflow.

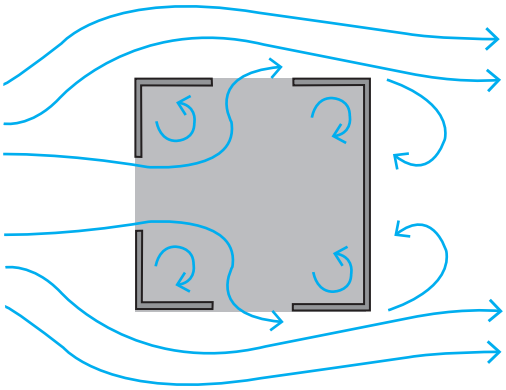


FIGURE 8.44 Wind direction inside a space is affected by the position of the openings.

The best location for an inlet is usually close to the vertical and longitudinal center of a wall that is perpendicular to the wind, where the pressure is highest. The best location for the outlet should be in the low pressure zone. The outlet can also be placed high, near the ceiling, to take advantage of a stack effect, if any.

Givoni (1976) suggests that the best ventilation in the space (in terms of overall air movement and homogeneous distribution) is obtained when the airflow changes direction inside the room (Figure 8.44) by not aligning the outlet windows with the inlet windows. Sobin (1981), however, found that a change in air flow direction sometimes substantially reduced air velocity.

To achieve sufficient natural ventilation inside the building spaces, it is recommended to have the openings toward the longest façades, which should be facing the wind. Windows should be on both sides of the space with the longer side of the building facing predominant wind directions, creating larger high-pressure and low-pressure zones on either side of the building and shorter routes for the air to traverse (Figure 8.45). Also, it is recommended for the windows to be at least 15% of the floor area to provide the necessary air changes and air movement for comfort, and some codes require all naturally ventilated spaces to be at least 20′ from a window. More openings in the negative pressure zone of a space usually increase ventilation flow. However, in spaces with higher occupation densities or more internal heat gains, these openings should be larger.

It is always recommended to have windows on at least two external walls of each space. However, when the room has only one external wall, this wall should have two windows, placed at the far ends

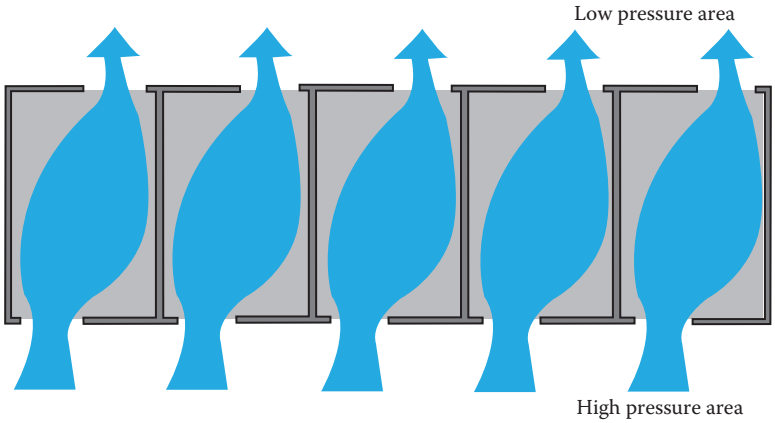


FIGURE 8.45 Aligned rooms can capture more air.

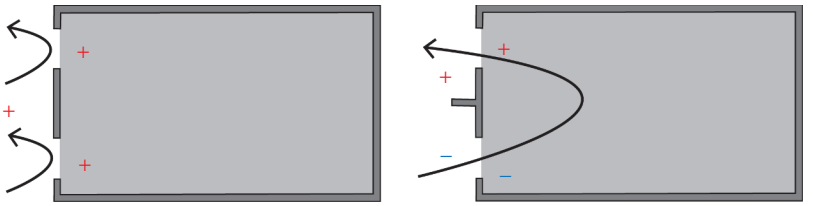


FIGURE 8.46 When windows are on the same façade, fins can be used to increase air velocity.

of the wall to achieve some difference in pressure and internal airflow through the space. It is also possible to increase airflow by changing the pressure around windward windows with wing walls or fins (Figure 8.46). If the wind is hitting façades without openings, most of the other windows will not have sufficient pressure to generate any significant cross-ventilation. In this case, pressure differences can be generated with vertical elements such as fins or vegetation that are perpendicular to the wall.

The angle of the inlet to the wind affects the air flow rate. For most of the windows, orientation of inlets at 90° to the wind provides the highest average indoor speed ratio. However, the best ventilation does not always occur when the window is perpendicular to the wind direction. Givoni (1994) suggests that buildings exposed to oblique wind along the windward walls create different pressures in the windows located in these walls, and the air can enter through the upwind window and exit through the downwind window. Certain combinations of inlet characteristics (especially shape) provide good results at 90°, but can also provide equal or better ventilation in oblique (up to 45°) winds than they do in normal (90°) winds. These windows would probably provide better overall ventilation because wind changes direction, and are often probably a better selection than a window that has better performance but with only one direction. Perpendicular winds with cross-ventilation in a room produce an average wind speed and internal maximum speed double that of windows on one side only.

8.5.3.2.2 The Effect of the Shape of the Windows on Ventilation

Windows with horizontal proportions generate higher indoor air velocities and catch a larger range of wind directions than vertical shapes (Cook, 1986; Sobin, 1981; Ghiabaklov, 2010). These windows are especially beneficial in locations where changes in wind pattern are more prevalent.

In all cases, windows should be accessible and operable so that users can control and direct winds according to ventilation needs.

8.5.3.2.3 The Effect of Window Obstructions

Internal divisions should not create barriers to inlet openings. If there are partitions, they should be perforated, less than full height, or have openings to permit the flow of air. Fly screens also reduce air speed, especially wire or cotton mesh. Smooth nylon or other plastic screens offer the least resistance. With higher air velocities, a wind screen's effect reducing the air velocity is more noticeable than with lower velocities.

Van Straaten measured the reduction in air velocity produced by screens and found that it depended on the incident wind speed, with a higher percentage reduction when the velocity was lower. For a 0.7 m/s (1.5 mph) wind, the airflow was reduced by 60%, while in a 2.7 m/s (6 mph) wind the reduction was only 28%. This difference is possibly due to the reduction of the wake region behind a cylinder as the Reynolds number increases. Internal airspeeds can only be predicted.

8.5.3.2.4 Building Shape and Ventilation Induction to the Inside

In warm, humid climates, the main purpose of ventilation is to provide maximum penetration and air changes with significant indoor air velocities. In hot, dry climates, the control of ventilation to provide night cooling is the main purpose. The main building elements that affect the ventilation

pattern are the height and length of the building and its roof slope, and it is important to consider the following variables in designing for wind:

An increase in the building's width enlarges the surface exposed to the wind while the depth of the wind shadow or calm zone remains constant.

An increase in the building's height provides higher speeds in the upper levels but, at the same time, increases speeds toward the first floor. This effect is even more accentuated in buildings with free flow areas on the ground floor.

A reduction in the width–height relationship increases the dimension of the wind shadow or calm zone.

If the roof's slope facing the wind has an angle above 30°, there will be an increase in the depth of the calm zone.

When the roof's slope is opposite the wind and below 30°, the increase in the dimension of the calm zone will not be significant. An increase in the slope above 30° will not provide any additional calm zone.

If the slope of a gable roof increases, the height and depth of the wind zone also increases.

Eaves on the leeward side have little effect on the wind shadow; however, they do affect airflow when facing the wind, contributing to capture the wind. Usually eaves and canopies over the window deflect the indoor airflow upward. If they are separate from the wall, then they will increase the air stream and promote air penetration inside the building.

As the angle between the wind direction and the largest dimension of the building (regardless of the shape) approaches 90°, the calm zone will also increase.

The following considerations should also be taken into account:

If the openings are at the same level and near the ceiling, most of the airflow will stay toward the top area of the space.

Openings at the ridges of gable roofs are useful in open-plan buildings because they produce suction effects that allow the hot air to exit.

8.5.3.2.5 The Effect of the Area Surrounding the Building

It is important to take advantage of the topography, landscape, and building surroundings to redirect the airflow and to ensure maximum exposure to the breeze. Garden elements such as trees, bushes, fences, or low walls can be used to reconduct breezes and to avoid stagnant air pockets.

If landscaping features are placed very near the building and windows, they may reduce the wind speed and modify the airflow pattern; but if they are placed at the sides of the window, they can act as wing walls, creating a higher positive pressure and increased airflow through the building. Also, wind speeds under tall trees are usually higher than toward the crown.

9 Passive Cooling Systems

All buildings are heated up during the day by the effects of solar radiation (sol) and cooled during the night by convection and radiant loss to the sky. In warm climates, the average indoor temperature is generally higher than the outdoor average temperature because the heat gains are usually higher than the losses.

According to Givoni (1994), there is a difference between bioclimatic architecture and passive cooling. Bioclimatic design consists of appropriate architectural design to keep the building from overheating or overcooling and can minimize the difference between the indoor average temperature and the outdoor average temperature, but cannot lower the indoor average temperature below the outdoor average values. Chapter 8 discussed the strategies for reducing overheating and overcooling in buildings. This chapter deals with passive cooling techniques, which are the only way in a hot climate to achieve average temperatures inside a building lower than outdoors unless mechanical or active techniques are used. In a cold climate, we would need active or passive *heating* techniques.

9.1 DEFINITION OF A PASSIVE COOLING SYSTEM

A passive cooling system is capable of transferring heat from a building to various natural heat sinks (Givoni, 1994). To achieve this, the building must have special design details, generally in some part of the envelope. Passive cooling systems provide cooling through the use of passive processes, which often use heat flow paths that do not exist in conventional or bioclimatic buildings.

A building designed using bioclimatic principles is a precondition for the application of passive cooling systems. If the building is not *bioclimatically* designed, then the passive systems will not run efficiently because they will need more energy to cool or heat than if they were already designed efficiently.

9.2 CLASSIFICATION OF PASSIVE COOLING SYSTEMS

Passive cooling systems can be classified according to the different heat sinks that are used (Givoni, 1994): ambient air (sensible or latent), upper atmosphere, water, and undersurface soil. Different cooling strategies as described in the following can be used to take advantage of these heat sinks (Givoni, 1994):

Comfort ventilation: providing direct human comfort, by moving ambient air, mainly during the daytime (sensible)

Nocturnal ventilative cooling: opening the building to cool the structural mass of the building interior by ventilation during the night and closing the building during the daytime (sensible)

Direct evaporative cooling: mechanical or nonmechanical evaporative cooling of air, which is then introduced into the building (latent)

Indirect evaporative cooling: evaporative cooling of the roof so that the interior space is cooled without elevation of humidity (latent)

Radiant cooling: transferring heat from the building to the upper atmosphere during the night hours

Soil cooling: cooling the soil below its natural temperature in a given region and using it as a cooling source for a building by some type of heat transfer mechanism

Cooling of outdoor spaces: cooling techniques that are applicable to the air of outdoor spaces adjacent to a building, usually using some sort of water evaporation or some sort of expenditure of energy.

This classification is useful because it relates the building systems with the heat sinks (Table 9.1). The applicability of a given cooling system depends on the specified limits of the indoor climate, which varies with the type of building and outdoor climate.

According to Cook (1986), the term *passive* as applied to the integral heating and cooling of buildings was invented in the United States. It generally describes a form of space conditioning without the use of parasitic power sources. Passive systems are driven primarily by natural phenomena. While conventional solar heating and cooling systems for space conditioning are active in their uses of motorized mechanical components to move fluids and air, these buildings are passive because they use few conventional sources of energy.

Passive space heating is driven only by the sun and was named first. *Passive cooling* is its counterpart. While passive heating uses the sun as a single solar heat source, passive cooling embraces several heat sinks and a wide variety of bioclimatic practices in building design; so, it is more complex and harder to classify. Passive cooling is implemented when temperatures are above the comfort zone (to the right) and the building gains more heat than it loses.

Not all passive cooling or heating systems are applicable in all types of climates, and it is important to understand the most favorable climatic variables. The implementation of each of the systems depends on specific climatic conditions such as relative humidity (RH), temperature, and radiant conditions. Figure 9.1 shows the areas in which passive cooling would be useful. These conditions depend on the nature of the process; some systems will work better under some conditions. It is important to understand when it is appropriate to use each system. The best way to determine when it is more beneficial to implement a particular strategy is to use Givoni's psychrometric chart with the passive strategies overlaid on it (Figure 6.11).

TABLE 9.1
Relation of the Heat Sinks with the Passive Cooling Strategies

Building System	Heat Sinks
Comfort ventilation	Ambient air
Nocturnal ventilative cooling	Ambient air
Direct evaporative cooling	Ambient air
Indirect evaporative cooling	Ambient air
Radiant cooling	Deep space
Soil cooling	Earth
Cooling of outdoor spaces	Ambient air or water

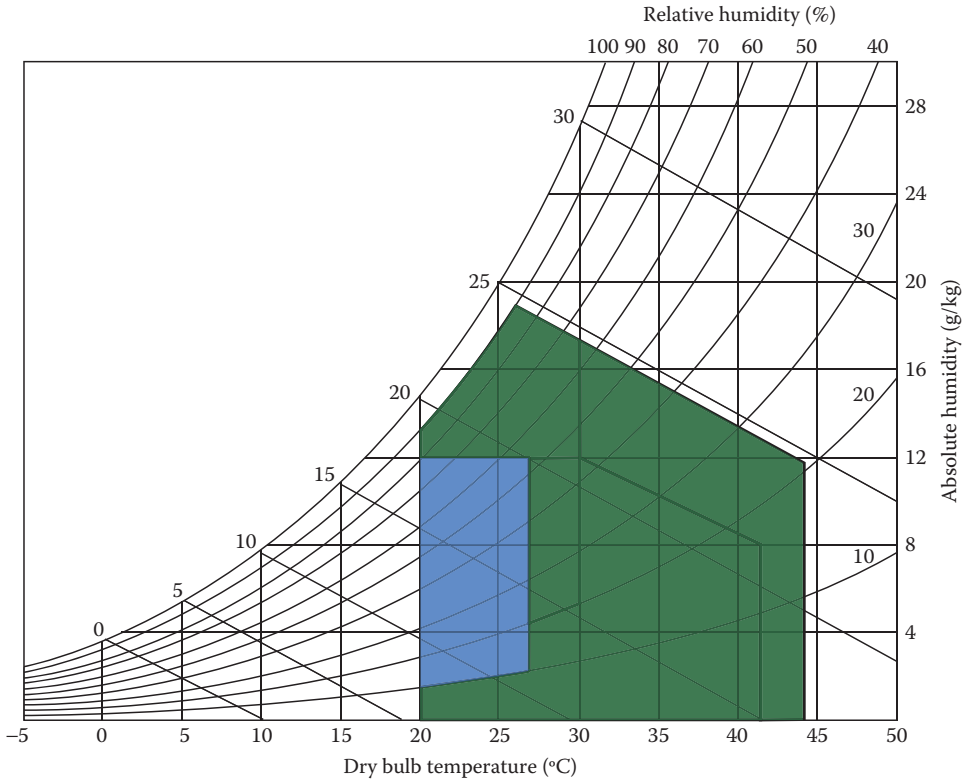


FIGURE 9.1 Outdoor conditions for which passive cooling strategies will help achieve thermal comfort.

9.3 AMBIENT AIR AS A HEAT SINK (SENSIBLE COMPONENT)

The atmosphere is also a medium of heat transfer, primarily through convection. Cooling by ventilation to the atmosphere is the simplest way to remove heat from buildings, and it is the most common passive cooling method. Indirect and direct evaporative cooling systems are also included in this general group.

Ventilation can be used for three completely different functions in a building: (1) cooling the human body, (2) cooling the structural mass of the building, and (3) indoor air quality (IAQ). Each of these has different requirements that affect the building and the ventilation systems. Good IAQ is usually an indirect positive product of ventilation systems. Comfort ventilation is an additional resource that can be implemented to extend the comfort zone to temperatures above the limit for still air. When outdoor air temperatures are lower and more suitable for sensible cooling, structure cooling can be put into effect, usually as nocturnal ventilative cooling.

9.3.1 Comfort Ventilation

Comfort ventilation provides direct human comfort. This is the simplest and most common strategy to improve comfort, and humans have historically relied on it for generations. Comfort ventilation is applicable when still air temperatures seem to be too warm, because air movement extends the

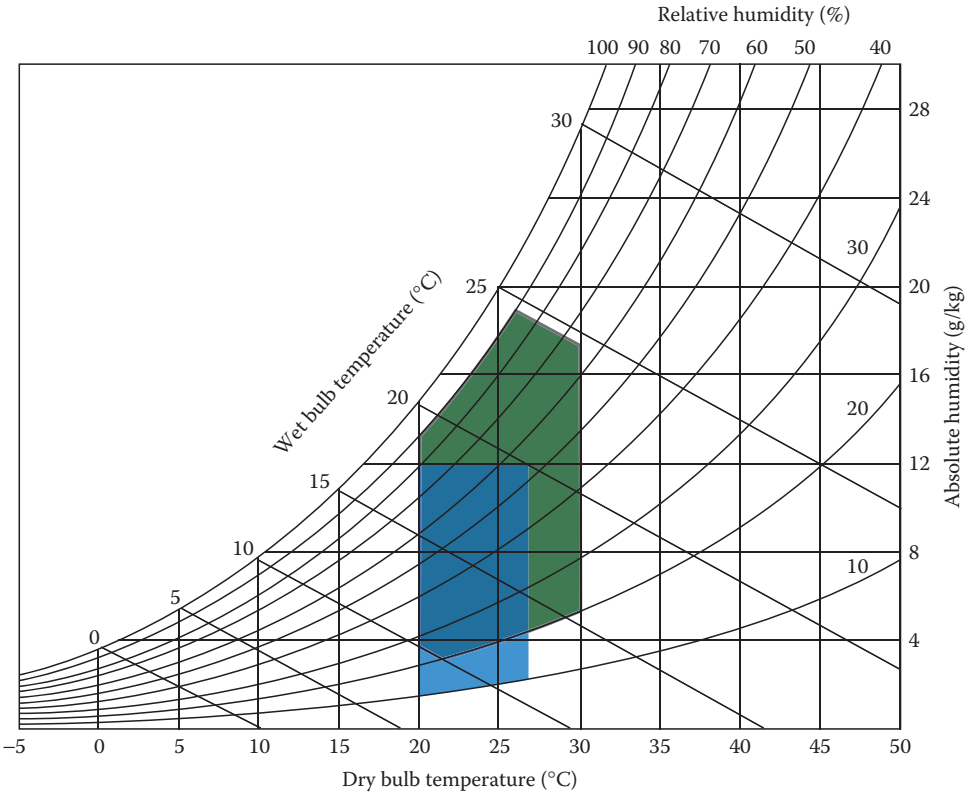


FIGURE 9.2 Applicability of ventilation to achieve thermal comfort.

comfort zone upward beyond the limit for still air. This air motion can be generated by ventilating the space with outdoor air but can also be produced by circulating air inside the space using a ceiling or portable room fan. The area in the psychrometric chart in which we can achieve thermal comfort by providing natural ventilation is indicated in Figure 9.2.

Using the air as a cooling source may be as simple as opening a window, but "designing" the window for the necessary amount of airflow and air change rate can be a more complicated task. Effective interior convective air motion rates are seldom more than one-tenth of the speed of the natural outdoor motion, even if the window is properly designed (Cook, 1986). It is usually recommended to have air speeds between 10 and 45 ft/min (0.06–0.25 m/s), regardless of whether the air is replaced or recycled, to achieve a sense of freshness in the space.

Increasing the air motion raises the boundaries of the comfort zone but in a nonlinear fashion. According to the Florida Solar Energy Center, there is a benefit of 4°F with air velocities between 100 and 150 ft/min (0.57 and 0.85 m/s) compared with still air. Figure 9.3 describes the optimal summer comfort lines for various air speed levels for rooms where the mean radiant temperature equals the dry-bulb temperature (DBT) and where persons clothed in summertime clothing (clothing level [CLO] = 0.5) are performing light office work (metabolic rate [MET] = 1.2). The optimal comfort lines are drawn between the RH lines of 20% and 80%, which are the limits set to reduce health problems and the generation of mold and mildew. The center of the comfort zone with still air [air velocity below 20 ft/min (0.1 m/s)] and 60% RH will be at 76°F (24°C). The shaded zone indicates the comfort zone where 80% of the population will be comfortable under still air conditions. The 80% comfort zone boundaries for an air speed between 150 and 300 ft/min (0.8–1.5 m/s) can be obtained by connecting the dotted and square symbols.

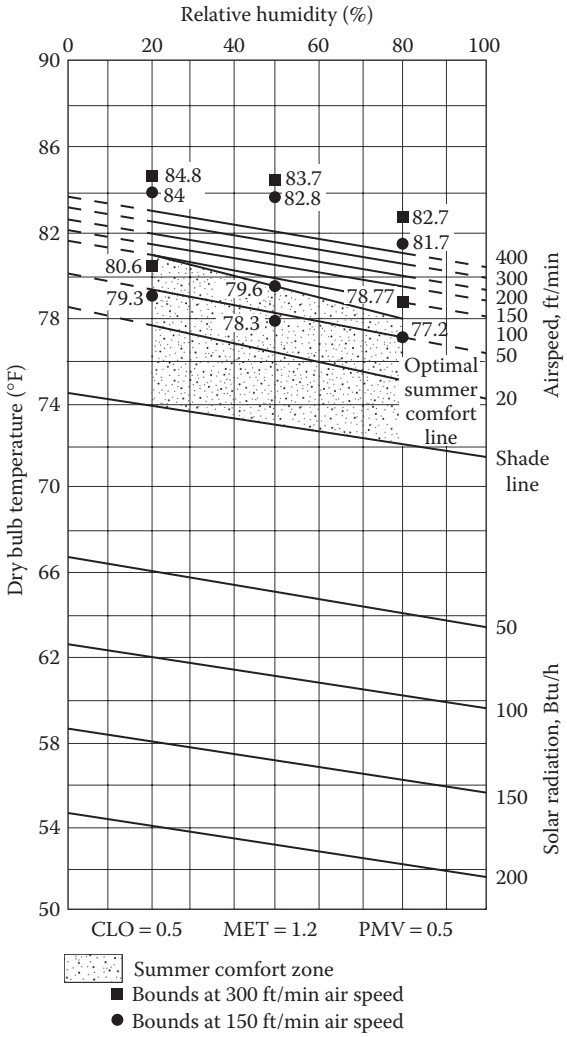


FIGURE 9.3 FSEC comfort chart, showing change in optimal comfort line for various air speeds. CLO, MET, and PMV refer to clothing level, metabolic rate, and predicted mean vote, respectively. (From Cook, J., *Passive Cooling*, MIT Press, Cambridge, MA, 1986.)

The disadvantage of comfort ventilation is that it does not lower indoor air temperature but counts on increasing comfort by elevating sweat evaporation from the skin. Air movement must be constant, especially when air temperatures are outside the comfort zone. The temperature up to which the body can still be comfortable limits the applicability of comfort ventilation. Therefore, ventilation can be applied only when indoor comfort can be experienced at the outdoor temperature with acceptable indoor air speed. Assuming that an indoor air speed of 1–1.5 m/s (200–300 ft/min) can be achieved either by natural passive or by active ventilation, Givoni (1998) proposes this outdoor value to be between 27 and 32°C (80.6–89.6°F). Above this temperature, air movement will not be useful for comfort, and as humidity goes up, it becomes more difficult to achieve thermal comfort with the same air velocity. Thus, the upper limit of the comfort zone goes down as the air temperature goes up (Figures 9.2 and 9.3). I assumed a practical upper limit of around 30°C to account for inefficiencies in the provision of ventilation.

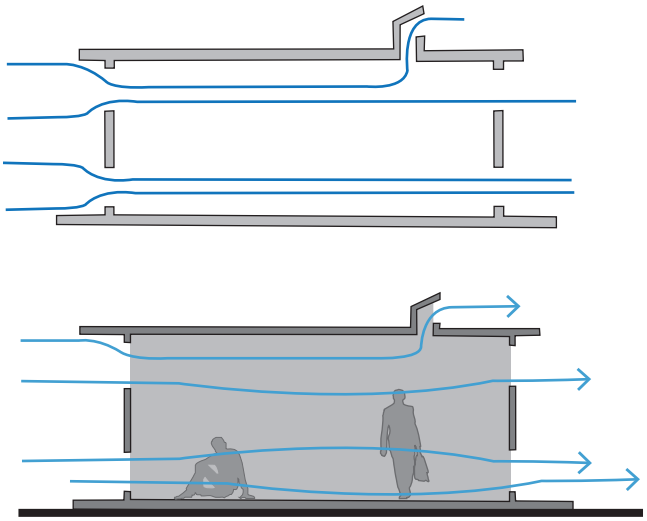


FIGURE 9.4 Windows provide air movement through the space at different heights.

Comfort ventilation is the most common strategy in a warm and humid climate. The archetype of a building for a hot and humid climate is a building that has low mass and large windows to maximize air movement. However, even heavy-mass buildings that are continuously ventilated could have lower maximum temperatures than low-mass buildings in many hot climates with different levels of humidity (Givoni, 1998), even though thermal lag could be a problem.

Comfort ventilation can occur by pressure differences acting on inlets and outlets (natural ventilation) or by mechanical means (forced ventilation). In many places, because of its unpredictability, the wind cannot be relied on to provide adequate air motion. In these cases, fans can be used to generate air movement inside the building or to increase the exchange of air between the indoors and the outdoors. Ceiling fans can easily generate air speeds above 200 ft/min, and whole-house fans can generate up to 20 air changes per hour. An effective strategy would combine natural ventilation to provide air exchange (building cooling) with ceiling or portable fans for air motion (people cooling) if natural ventilation could not provide sufficient air velocities. The fans can continue to operate, providing air movement and can reduce the cooling load when air conditioning is needed (Figure 9.4).

9.3.2 Nocturnal Ventilative Cooling

Nocturnal ventilative cooling occurs when an insulated high-mass building is ventilated with cool night outdoor air so that its structural mass is cooled by convection from the inside, bypassing the thermal resistance of the envelope (Figure 9.5). During the daytime, if there is a sufficient amount of cooled mass and it is sufficiently insulated from the outdoors, it will act as a heat sink, absorbing the heat penetrating into and generated inside the building and thus reducing the rate of indoor temperature rise (Figure 9.6). This ventilation system can be either fan forced or natural, through windows that are opened and closed at appropriate times. During overheated periods, the ventilation system (windows or fans) must be closed to avoid heat gains by convection. Nocturnal ventilative cooling is a well-known strategy that has been used for many years, mostly in warm and dry climates. In these climates, buildings with thick walls were cooled during the night and acted as heat sinks during the day. Night ventilation reduces internal maximum temperatures, peak cooling loads, and overall energy consumption and has been well documented (Allard and Santamouris, 1998; Cook, 1989; Givoni, 1994; Santamouris and Asimakopoulos, 1996; Grondzik, Kwok, Stein, and Reynolds, 2010).

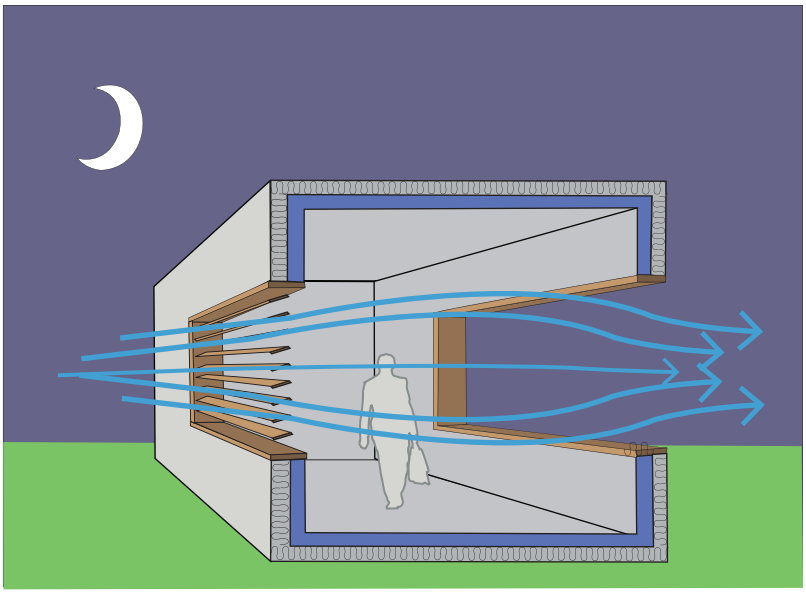


FIGURE 9.5 Nocturnal ventilative cooling (nighttime).

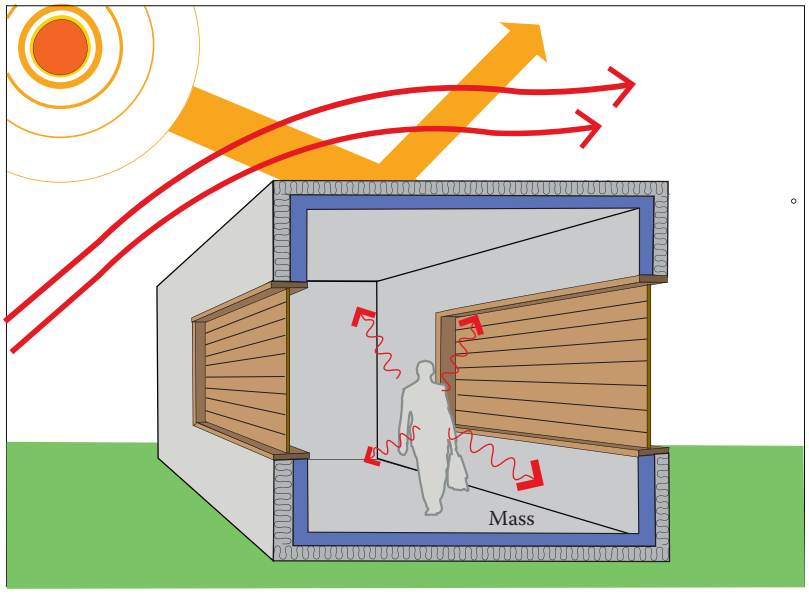


FIGURE 9.6 Nocturnal ventilative cooling (daytime).

The applicability of nocturnal ventilative cooling is limited to a certain range of conditions (Givoni, 1994), which are a function of the needs of the occupants and climatic conditions. Occupants affect decisions such as opening or closing the windows during the night and the desirable comfort levels. The climatic parameters that determine the effectiveness of nocturnal ventilative cooling are the minimum air temperature, which determines the lowest temperature achievable; the daily temperature swing, which determines the potential for lowering the indoor maximum below the outdoor maximum; and the water vapor pressure level or humidity, which determines the upper temperature limit of indoor comfort with still air or with air movement (Geros, Santamouris, Tsangasoulis, and

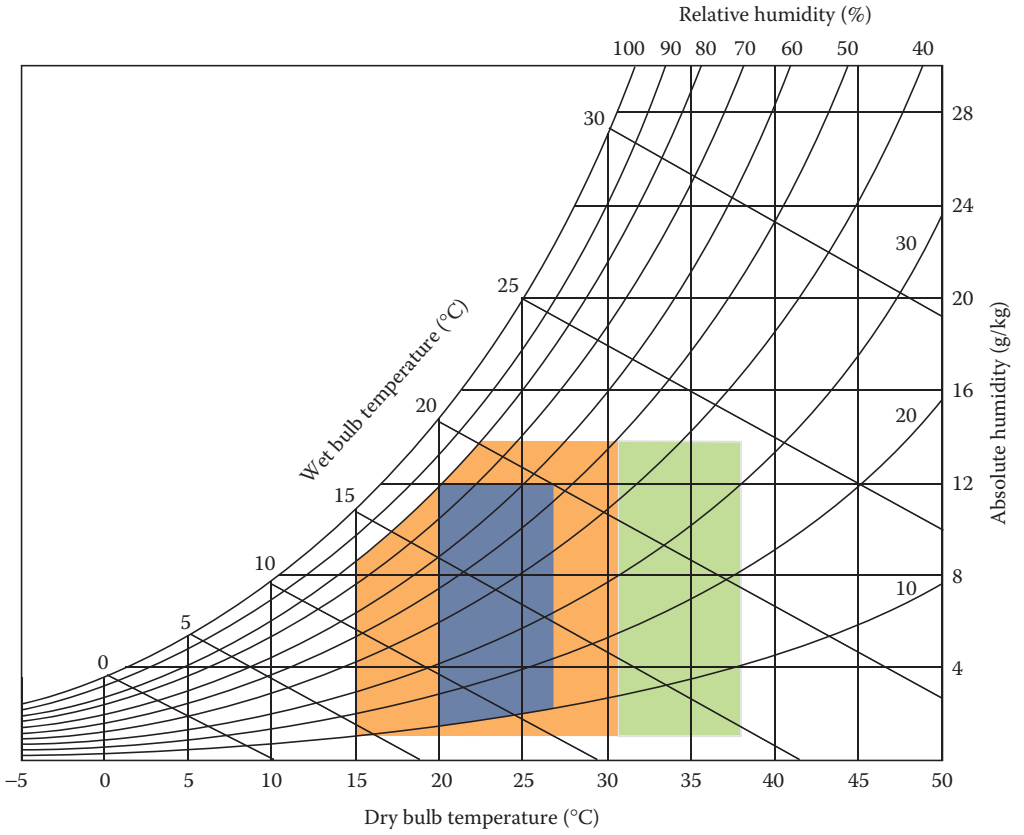


FIGURE 9.7 Applicability of night ventilation with thermal mass (green) or thermal mass only (orange).

Guarracino, 1999). Since the outdoor daily temperature swing usually increases as the air humidity is reduced, the humidity of the air is one of the practical determinants of the applicability of different ventilation strategies. Night ventilation is applicable in regions with a diurnal temperature swings above 15°C (27°F), daytime temperatures between 31°C and 38°C (90°F–97°F), and night temperatures below 20°C (68°F) (Figure 9.7). If the maximum temperature is above this value, there is not enough swing, or it is too warm at night, then other strategies should be applied during the hottest hours (Givoni, 1994). These conditions are typical of hot and dry climates, making night ventilation one of the preferred strategies in these climates. Even though this strategy is usually not considered effective in warm humid climates, Machado and La Roche (1999) explored the implementation of night ventilation as a passive cooling option for buildings in warm, humid climates.

The psychrometric chart with the area delimitated for night ventilation can serve as a general indicator of applicability. The main parameters that determine the performance of night ventilation can be classified in three broad groups: climatic parameters, building parameters, and technical parameters of the technique (Blondeau, Sperandio, and Allard, 1997).

In relation to the climatic parameters, several authors have proposed calculation methods, predictive equations, or rules of thumb to predict performance with different amounts of mass, ventilation rates, temperature swings, or outdoor average temperature. Givoni (1995, 1998) stated that the indoor maximum temperature in night-ventilated buildings follows the outdoor average temperature and proposed formulas to predict the expected indoor maximum temperature with different amounts of mass and insulation. Grondzik et al. (2010) proposed rules of thumb and calculation methods to determine the amount of heat that can be removed from a building with a

given amount and distribution of mass, during a typical day, for specific design conditions. Shaviv, Yezioro, and Capuleto (2001) proposes a tool to predict the decrease in the maximum temperature from the diurnal temperature swing as a function of the night ventilation rate and the amount of mass. Computer programs like Home Energy Efficient Design (HEED) allow users to determine the effects of mass, ventilation rates, and insulation on the indoor air temperature or the amount of air conditioning required to maintain a specified comfort temperature (Milne, Gomez, La Roche, and Morton, 2005).

In relation to building characteristics, the requirement is usually a minimum amount of thermal inertia, generally defined as a minimum amount of building mass required for thermal storage (Givoni, 2011). More thermal–structural mass increases the efficiency of the technique as the inertia of the building is increased, and the effect of night ventilation can be observed in the next day's lower and delayed indoor temperature profiles (Geros et al. 1999). A useful rule of thumb is that the thermal mass in hot and dry regions with daily temperature swings of 15°C–20°C can reduce the indoor maximum temperature 6°C–8°C below the outdoor maximum (Givoni, 1998). The interior planning of the building also plays a very important role, determining the obstruction level of the airflow of the air through the building (Geros et al. 1999).

The technical parameters related to the efficiency of night ventilation deal with the operation period and air change rate. There is agreement on the fact that heat gains by conduction through the building fabric, solar gains through window glazing, infiltration from warm outdoor air, and internal gains from equipment and occupants must be reduced. It is also well known that higher air changes are better than lower air changes, but there is no agreement on the ideal air change rate, and values range from 8 to 20 air changes per hour (Blondeau et al. 1997). If there is sufficient airflow, indoor temperatures close to the outdoor temperature can be achieved.

The operation of the ventilation systems in buildings (windows or fans) is usually controlled by timers or the occupant of the space who must rely on their experience or by thermostats that measure only indoor temperature. Little has been done on techniques to improve the performance of these ventilation controllers. Eftekhari and Marjanovic (2003) proposed a fuzzy controller that monitors outside and inside temperatures together with wind velocity and direction to open or close a window at various degrees to ventilate a building.

Even though their potential for cooling is well known, natural and hybrid ventilation strategies have not been investigated in the United States to the same extent as in Europe (Spindler, Glicksman, and Norford, 2002). This is partly because typical buildings in the United States, especially houses, do not have much mass to act as heat sinks, and the additional mass needed for ventilation is also associated with an increase in costs.

Because heat transfer by convection uses air as the transfer medium, it is proportional to the temperature difference between the interior and exterior of a building and the airflow rate. Equation 8.27 can be used to estimate the amount of heat transferred by convective effects.

If the outdoor temperature is higher than the indoor temperature ($T_o > T_i$), heat will flow to the interior of the building, thus heating the space; if outdoor temperature is lower than the indoor temperature ($T_o < T_i$), heat will flow to the exterior of the building (heat loss to the outside), thus cooling the space. As the temperature difference or the airflow rate between the interior and the exterior increases, the amount of heat transferred between the indoors and the outdoors will increase. Thus, if a building is to be cooled when the outdoor temperature is lower than the internal temperature, it must be designed to have the maximum amount of air changes per hour. The factors that affect the airflow in a building are mostly related to the size and position of the openings.

Equation 8.26 indicates that to prevent the building from overheating in hot climates, it is important to block heat gain from natural or forced ventilation and infiltration. This usually means that in warm climates, the building must be closed when the outdoor temperature is higher than the internal temperature ($t_o > t_i$) and must be opened when the outdoor temperature is lower than the internal temperature ($t_o < t_i$). However, factors such as the need for physiological cooling due to a high RH of the air can also affect the decision to open or close a window.

9.3.3 Smart Ventilation

La Roche and Milne (2001, 2002, 2003) developed and tested at the University of California, Los Angeles (UCLA) a smart controller that optimizes the use of forced ventilation for structure cooling in a building. This controller used a set of decision rules to control a fan to maximize indoor thermal comfort and minimize cooling energy costs using outdoor air, the greatest potential source of free cooling energy in most California climates. This controller knows when to turn the fan on and off to cool down the building's interior mass so that it can "coast" comfortably through the next day. Thus, the need for air conditioning can be greatly reduced or even eliminated. However, the performance of this system can be seriously compromised if the previously mentioned design considerations are not taken into account regarding the amount of mass and the control of solar radiation. The effects of these variables on the system were determined under different air change rates.

The experimental system consisted of a microprocessor controller connected to thermistors that measured temperature, a laptop computer connected to it that contained the control programs and collected and stored experimental data, the two test cells, and an active ventilation system that consisted of a 4-inch inlet and on the outlet side a 4-inch constantly running fan. The inlet damper was opened and almost closed in the experimental cell by a signal from the microcomputer, and the damper was fixed in an "almost" closed position on the control cell to also allow the same controlled amount of infiltration in each cell (0.7 air changes per hour).

Two identical test cells were built simulating the characteristics of typical California slab-on-grade houses. Only the characteristics that would affect the thermal performance of the ventilation system were included in the cells: the insulation level, the brick slab, and the glazing. Another simplification was that the cells had only a south-facing window so that they would receive the same amount of radiation at the same time. The cells were 122 cm (4 ft) wide by 244 cm (8 ft) long and 244 cm high and were oriented with the longest facade toward the east and west. The cells had 9.6 cm (3 inch) foam R12 insulation on the outside and 6.4 mm (¼ inch) gypsum board inside the walls and roofs with a U-value of 0.43 W/m^{2}K in the walls. The east and west walls had additional shading provided by an insulation panel separated 8 cm from the wall. A calibration series, with both cells under identical conditions, demonstrated that these panels eliminated the distortion caused by solar radiation in the morning and afternoon. The floor was hardboard placed on top of an insulation panel, and the roof had two layers of insulation with a U-value of 0.22 W/m^{2}K. There was a 61 × 61 cm (2 ft × 2 ft) double-pane window on the south side with a solar heat gain coefficient (SHGC) of 0.72 and a U-value of 4.25 W/m^{2}K (0.75 Btu/h ft^2 °F). The area of the window was 0.37 m^2 (4 ft^2) for a ratio of the glazing-to-floor area of 12.5%. The walls and windows were carefully sealed so that infiltration was controlled only by the fan and damper system.

One of these cells, with the smart operable venting system, was the "experimental" cell in which the air change rate varied between 0.7 and 3.9 air changes per hour. The other cell was the "control," with a fixed ventilation rate of 0.7 air changes per hour (Figure 9.8).

Different control rules were tested to determine which was more efficient using outdoor air to achieve thermal comfort. The controller rules that were tested were simple enough so that they could be built into a thermostat. Four variables were used to calculate the appropriate air change rate: indoor air temperature, outdoor air temperature, comfort low, and comfort high. The first two measure the air temperature and the need for cooling. If the indoor temperature was higher than the outdoor temperature, then the airflow rate increased by opening the damper; if the indoor temperature was lower than the outdoor temperature, then the damper was closed to reduce the airflow rate. Comfort low and comfort high set the upper and lower limits of the comfort zone and determined the air change rate accordingly. If the air temperature was above the comfort zone, it was too warm to provide cooling, and if it was below the comfort zone, no additional cooling was needed. A wider comfort dead band reduced the energy needed for cooling.

Various control strategies were tested with different relationships among the variables (some rules did not use all variables), air change rates, and values for comfort low and comfort high, in

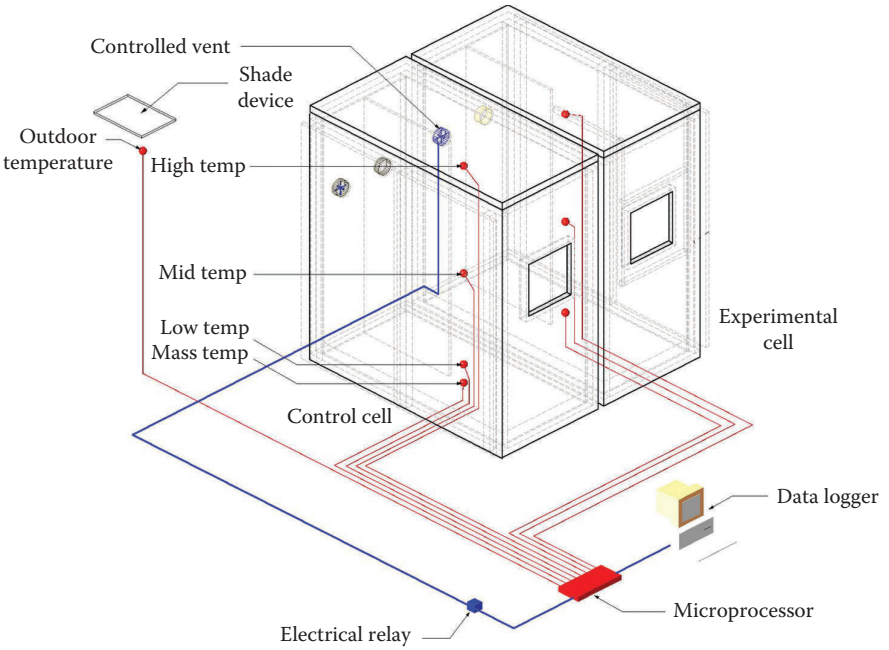


FIGURE 9.8 Experimental setup for the smart ventilation system.

summer 2000 and 2001, and are discussed in more detail in La Roche and Milne (2001, 2002, 2004) and La Roche (2005a). The rule that achieved the most hours in comfort and the lowest maximum temperatures in the experimental cell is expressed as

$$\text{If } T_o < T_i \text{ and } T_i > C_{f_\text{low}} \text{ and } T_i > C_{f_\text{high}} \quad \text{then fan ON} \quad \text{else fan OFF} \tag{9.1}$$

where:

T_o is the temperature outside
T_i is the temperature inside
C_{f_low} is the comfort low at 18.33°C (65°F)
C_{f_high} is the comfort high at 25.55°C (78°F)

This is the rule that was then used to determine the effects of the mass and window size. A snapshot of one of the series is shown in Figure 9.9.

Research with these test cells at UCLA demonstrated that it was possible to use smart controllers to cool a test cell in Los Angeles and thus to have a building with reduced internal loads. The factors that affect the performance of this system are the air change rate, the value of comfort low, the thermal capacity of the building, and solar gains through the windows.

A higher air change rate during the cooling period increases the amount of heat that is flushed out of the building, lowering the temperature of the mass and the maximum temperature for the next day. The test cells that had the smart ventilation system and could increase the air change rate when needed always performed better than the test cells with a fixed infiltration rate. The system performed better with maximum air change rates of 15 air changes per hour instead of 4 air changes per hour, but satisfactory results were still achieved with maximum air change rates of only 4 air changes per hour.

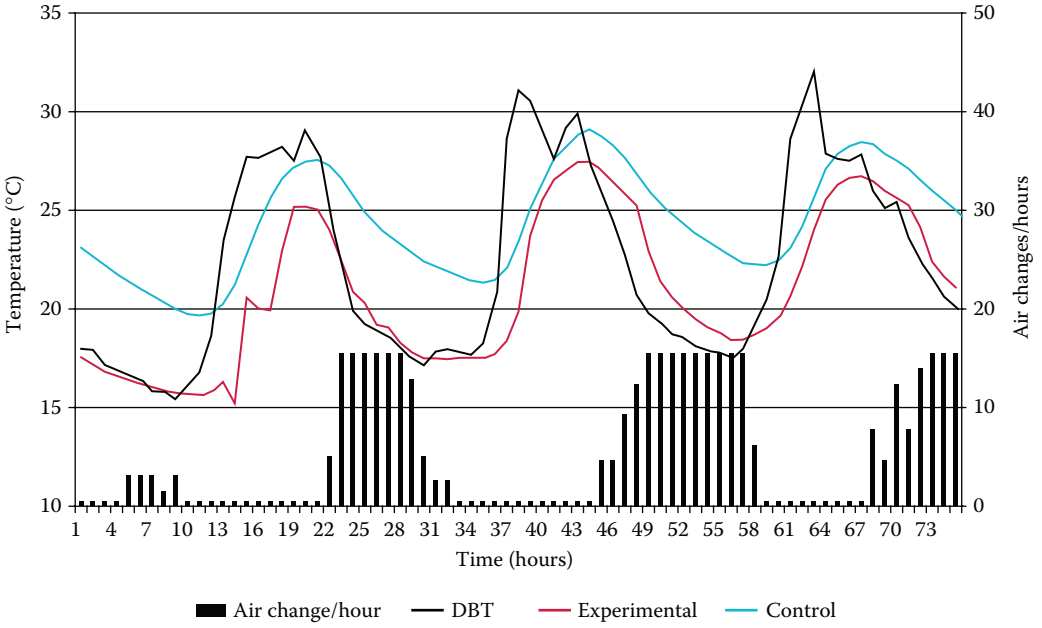


FIGURE 9.9 Temperature and air changes in an experimental series in the smart ventilation system.

With a smart controller, not only the lowest outdoor temperature but also the value of comfort reveals the potential for cooling. After the indoor air temperature is cooled to this value, the damper is closed and the indoor air temperature is maintained, even though the outdoor temperature could descend below this point. If the value of comfort low is reduced, the indoor maximum temperature of the building the next day is also reduced. To achieve maximum cooling the next day, the value of comfort low should be set to the minimum temperature that can be tolerated at night; 18.33°C proved to be a useful number, but series with a comfort low of 15°C performed even better.

The amount of mass inside the building affects the thermal inertia so that the cooling effect, which is mostly at night, can be translated to the next day, thereby reducing the maximum temperatures inside the building. Two amounts of mass were tested using the smart controller. With a slab-on-grade building as defined by the California energy code, the difference between the control and the experimental cell is 2.2°C. When more mass is added to the experimental test cell, the temperature difference increases to 3.1°C. Even with additional mass, the rate of 3.9 air changes per hour seemed sufficient to cool the amount of mass used in the experiment to the comfort low value of 18.33°C.

Solar radiation is an important factor that reduces the performance of the cooling system if its incidence inside the space is not controlled. In all the series and with all indicators, an increase in the shaded area of the window size was followed by an improvement in the performance of the system. The performance was inversely proportional to window size, and the performance was also consistently better when the smart ventilation system was used instead of the fixed infiltration system.

In all cases, comfort was improved by more mass, smart ventilation controllers, or smaller windows. Even though the systems with "no windows" exhibit the best performance, windows are important sources of natural light and views in buildings, so they obviously must not be completely eliminated. South-facing windows are also important assets for winter heating in mild, mid-latitude climates. Shading systems should be designed to block solar radiation from these windows in the summer and to increase the cooling performance of the system.

This smart controller has the additional advantage of being able to adjust the ventilation rate as needed in the building and when cool enough temperatures are available outdoors. The hours

in which the air change rate must be reduced or increased vary from day to day, and the system sometimes turns on during the day if conditions are favorable. A smart controller provides additional cooling compared with traditional systems that have fixed operating times, because it knows when it will be effective to cool with outdoor air. This improves the performance of the cooling system, reducing the amount of mass needed. Furthermore, the cooling system helps to maintain indoor temperatures inside the comfort band, reducing the number of overheated hours compared with the control cell. The system keeps the indoor air temperature inside the comfort zone by using outside air to cool whenever it is possible and using the thermal inertia of the mass to coast during the warmer hours of the day.

Because comfort low and comfort high in the system are also adjustable by the user, the user has control over his environment, and the system can be tailored to individual requirements, thus increasing the controller's performance even more. It would be a simple matter to add a thermistor to read outdoor temperature and to modify the microprocessor of a thermostat to implement these rules in a smart thermostat. It is hoped that these resources will inspire manufacturers to expand their product lines to offer these capabilities.

9.3.4 Effect of Shading on Smart Ventilation

Many buildings tend to be designed with an abundance of windows, which increases heat losses in the winter and also heat gains by solar radiation in the summer, creating uncomfortably warm indoor conditions when mechanical cooling is not used or increasing the energy used by mechanical cooling systems when it is used. Blocking this solar radiation in the summer reduces energy consumption and indoor temperatures. The same microprocessor controller that controls the fan is also tested to control automatic window shades and to minimize cooling loads. Commercially available electrically operated venetian blinds were used in this study. Already on the market, especially in Europe, are extendable and retractable awnings, vertical external operable louvers, internal operable draperies, and venetian blinds. However, these are not usually used with a microprocessor thermostat that can read indoor and outdoor temperatures and operate shading devices to optimize indoor temperatures.

As before, data from both the experimental cell and the unshaded control cell are automatically recorded every few minutes. These data can be input into spreadsheets and the results plotted as the experiments are in progress. The controller measures indoor temperature/outdoor temperature, and in these series, surface temperature of a metal plate in the south wall, which was used as a rudimentary detector of solar radiation. It is also preset with the upper and lower limits of comfort temperature. The controller also needs to know whether it is the heating or cooling season; however, our simulation studies imply that this can be calculated on the basis of average temperatures during the prior few days (Figure 9.10).

Summer Rule: In the summer, two conditions must be satisfied to close the shade. The first condition is that shading is provided whenever the indoor temperature is above 70°F, which is assumed as the shade line. The second condition is that a black south-facing metal plate (the window is also facing south) must be warmer than the air temperature. This indicates that the sun is facing that window and is receiving solar radiation.

Winter Rule: The shade system is used to avoid overheating of the building through the windows. The shade system is set so that the louvers will close if the indoor temperature is higher than a specified value, in this case 75°F (23.9°C), or 3°F lower than the value set for comfort high (78°F).

Many series were performed to optimize the performance of the different systems, and only one of these is presented as an example (Figure 9.11). Several equations were also developed to predict the performance of these systems (La Roche and Milne, 2001, 2002, 2003, 2004a, 2005).

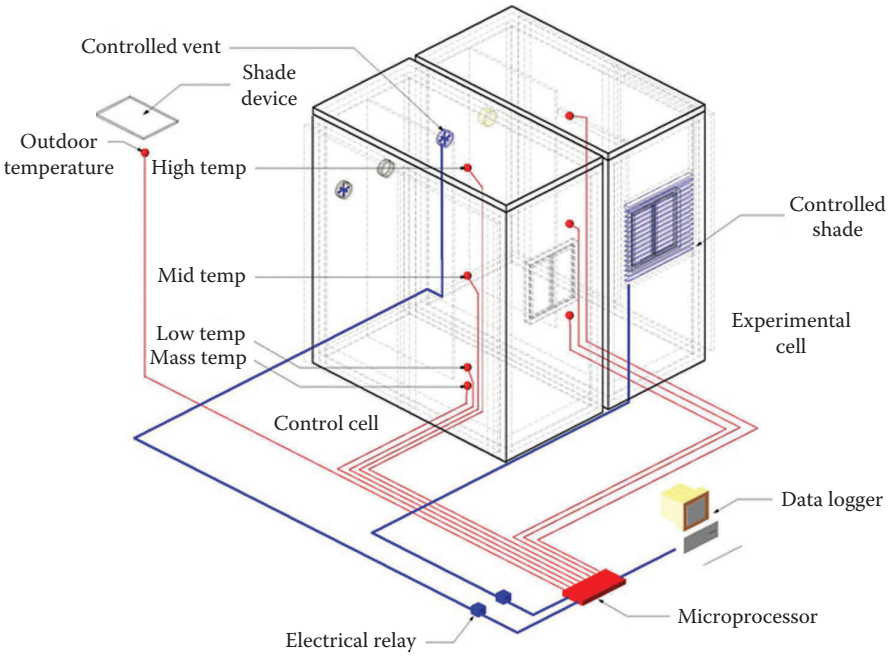


FIGURE 9.10 Experimental setup for the smart shading and ventilation system.

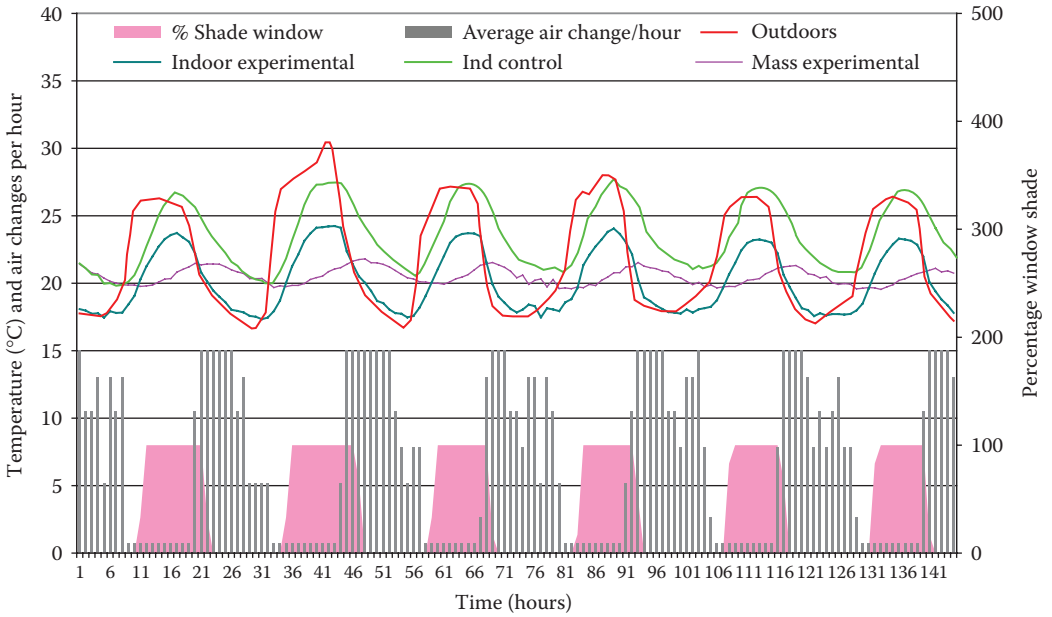


FIGURE 9.11 Example series with smart ventilation and smart shading.

9.3.5 Alternative Methods to Night Ventilate: Green Cooling

A living or green roof is a roof that is substantially covered with vegetation. Green roofs have been proven to have positive effects on buildings by reducing the stress on the roof surface, improving thermal comfort and reducing noise transmission into the building, reducing the urban heat island effect by reducing "hot" surfaces facing the sky, reducing storm water runoff, reoxygenating the air and removing airborne toxins, and recycling nutrients and providing habitat for living organisms, all of these while creating peaceful environments.

The positive thermal effects of green roofs are usually described by the reduction of the external surface temperature due to the effect of vegetation and the reduction of the thermal transmittance of the assembly, mostly due to the effects of insulation, usually placed between the sustaining material and the interior space of the building. A green roof without this added insulation has a low thermal resistance but does have thermal mass. Apart from providing protection against overheating, a green roof can also provide some cooling through the evaporative process in the plants (Del Barrio, 1998). Their vegetative matter absorbs solar radiation through the biological processes of photosynthesis, respiration, transpiration, and evaporation. However, the solar radiation that bypasses these processes can seep into the building envelope (Niachou, Papakoustantinou, Santamouris, Tsangrassoulis, and Mihalakakou, 2001).

Studies have demonstrated that a well-planned and managed green roof, with insulation, acts as a high-quality insulation device in the summer (Theodosiou, 2003). However, little has been done to take advantage of the mass of the green roof as a heat sink in temperate or hot climates. By reducing daily thermal fluctuations on the outer surface of the roof and increasing thermal capacity in contact with the indoors, green roofs can contribute to the cooling of spaces if the mass of the soil is cooled. Some research in this direction indicates the potential for reducing the cooling loads inside buildings (Eumorfopoulou and Aravantinos, 1998; La Roche, 2006c).

During the course of three summers, several green roofs were built and tested at the Lyle Center for Regenerative Studies at Cal Poly Pomona. The university is located about 30 miles east of Los Angeles in southern California, in a hot and dry climate with mild winters (Figure 9.12).

This section focuses on the cooling potential of green roofs combined with night ventilation by looking at the internal temperature of experimental test cells and in a full-size residential building.

Three test cells with a dimension of 1.2 m × 1.2 m × 1.2 m were built using 2 inch × 4 inch stud wall construction with drywall on the inside, plywood on the outside, and batt insulation in between for a U-value of 0.12 W/m^2 K. The exterior is white, and the three cells have 0.61 m × 0.61 m (2 ft × 2 ft) single-glazed windows facing south that were replaced by double-glazed windows in 2007 in the last series. All of the cells have 3.8-cm-thick concrete pavers as the slab (Figures 9.13 and 9.14).

The roof is the only difference between the cells. The first cell has a code-compliant insulated roof, with a U-value of 0.055 W/m^2 K, painted white; the second cell has an insulated green roof; and the third one has an uninsulated green roof (Figure 9.14). The growth medium in the uninsulated green roof is thermally coupled with the interior via a metal plate, while in the other green roof there are 10 cm of matt insulation between the space and the soil. Night ventilation is provided with a fan, and all of the cells are equipped with dimmers and timers to adjust the ventilation rate and start–end times.

The green roofs were of the extensive type. Two types were built. The first one, in 2005, was covered with Saint Augustine grass above a layer of 9.5-cm-thick soil with 2.5 cm of gravel and a plastic liner underneath. Drainage tubes were spread through the gravel with perforations that capture the excess water and drain it outside the building. The plastic liner was spread above a metal plate, supported by wooden joists. The metal plate assured thermal coupling between the mass and the

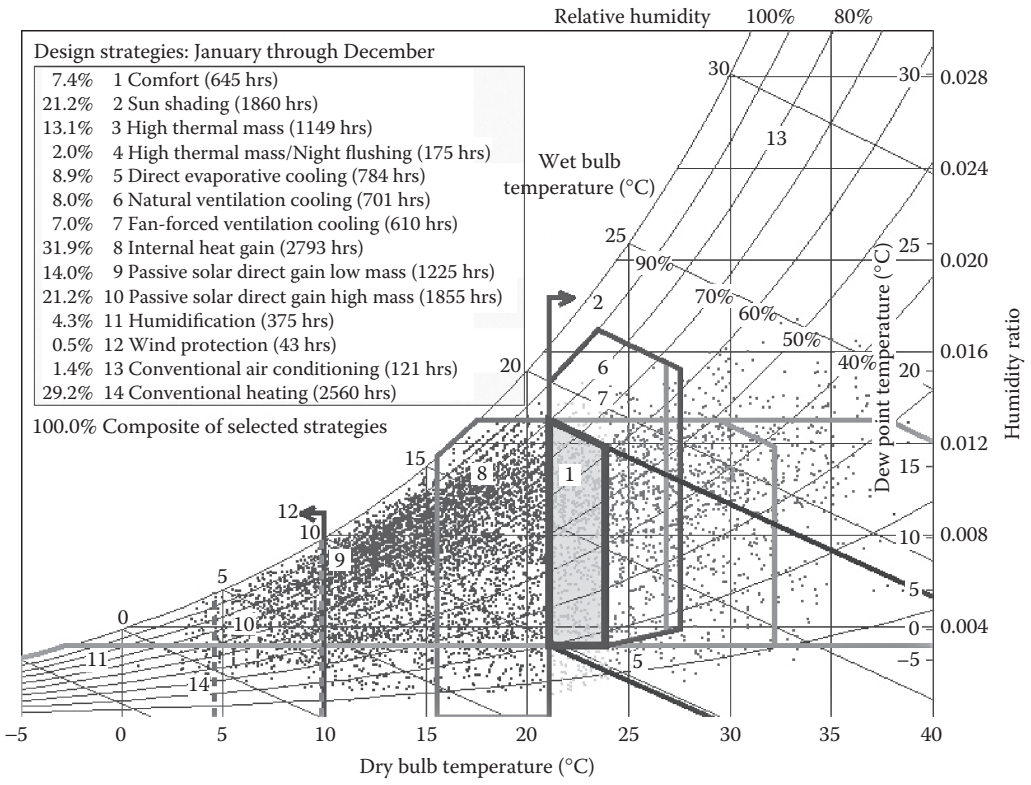


FIGURE 9.12 Pomona climate plotted in Climate Consultant.

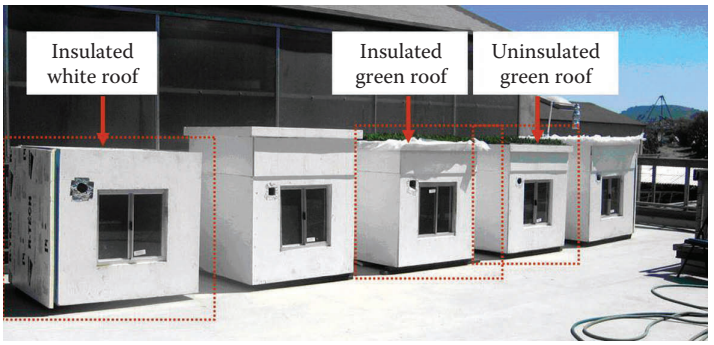


FIGURE 9.13 Experimental test cells at the Lyle Center for Regenerative Studies at Cal Poly Pomona.

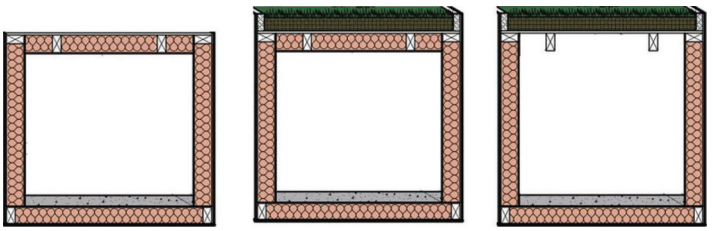


FIGURE 9.14 Section through experimental test cells used in the green roof experiments.

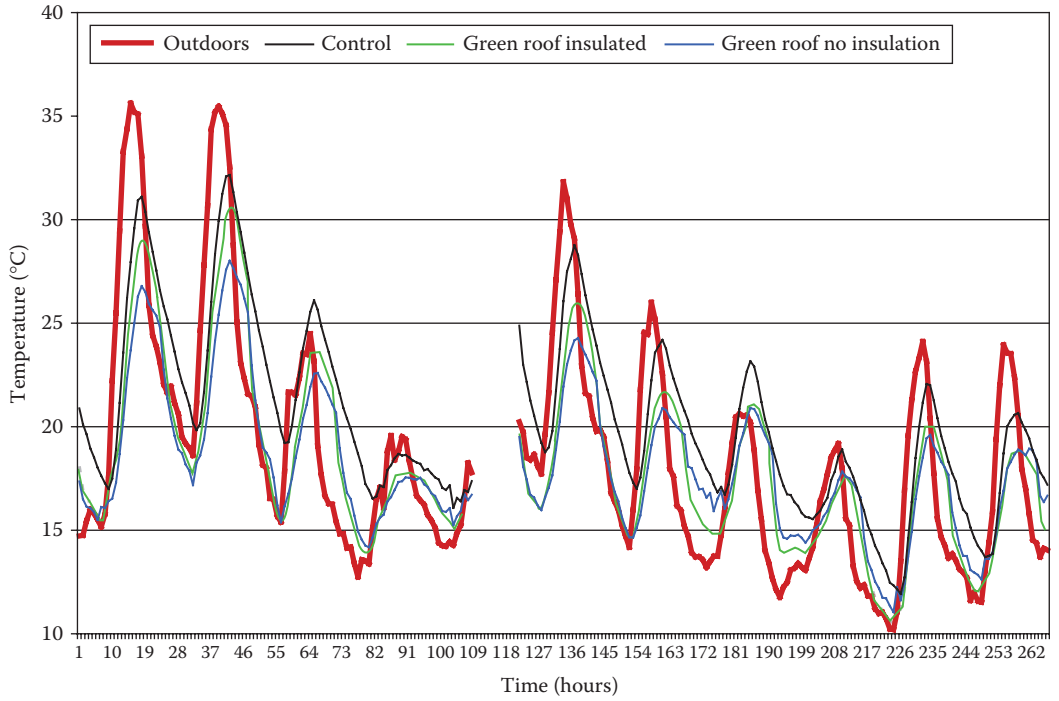


FIGURE 9.15 Control, insulated, and uninsulated green roofs series in 2005.

space underneath (Figure 9.14). The green roof in the cells was substituted by another one in 2007, designed so that it could be built on a large scale with minimal technology, low-cost materials, and little maintenance (Hansanuwat, Lyles, West, and La Roche, 2007 ; West and La Roche 2008). "Rice sack" tubular bags developed by the Cal Earth Institute were cut and filled with a growth medium containing 50% native soil and 50% perlite. These bags were placed above an impermeable layer of plastic, which was placed on top of the roof decking as a moisture barrier. Slits were cut into the topside of the bag, and sedums and succulents were planted, which had little need for water, maintenance, or soil depth. The bags were photodegradable to sunlight; thus, over time the surface of the bags disappeared and created a soil strata evenly distributed over the roof. This same system was also used in an affordable low-cost house prototype for Tijuana, Mexico, that was tested in fall 2008.

Many series were performed, one of which is shown as an example in Figure 9.15. This series initiated on September 7, 2005; there is no window. During the day, the values of the maximum temperatures in the insulated control cell are an average of 0.7°C below the outdoor temperature; in the insulated green roof, they are 2.6°C below the outdoor temperature; and in the uninsulated green roof, they are 3.6°C below the outdoor maximum temperature (Figure 9.15).

In 2008, the single-glazed window was substituted by a double-glazed window, shaded with a 60-cm overhang that provided complete shading during the summer noon hours and partial shading during the morning and afternoon hours. The Saint Augustine grass was substituted in 2007 by a succulent species that needed little water. Results of the tests in 2008 are consistent with previous series and also indicate that the green roof with no insulation performs better than the insulated green roof and the insulated white roof (Figure 9.16).

An uninsulated green roof combined with night ventilation can help cool a space in two ways: (1) the canopy layer reduces the effect of solar gains by reducing the sol–air temperature and (2) the growth medium acts as a heat sink.

Results of tests at the Lyle Center for Regenerative Studies, over several years with different types of plants, windows, and shading systems, consistently indicate that during the summer in this climate

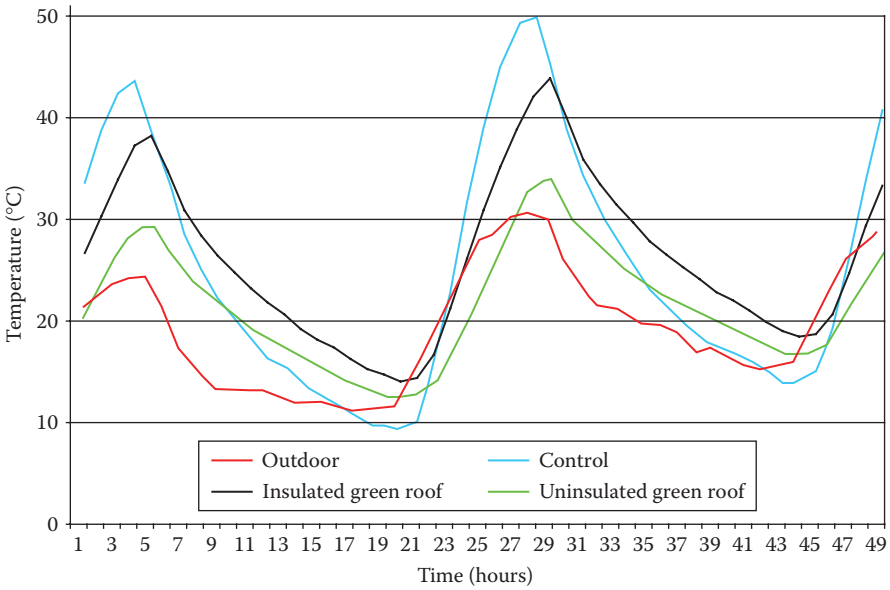


FIGURE 9.16 Two days in the 2008 green roof series.

the uninsulated green roof performs better than the insulated green roof and the insulated white roof. Thus, in a warm or mild climate with cool nights, it is possible to combine a green roof with night ventilation, coupling the soil layer with the interior of the building. The vegetation in the canopy layer improves the performance of the system by blocking solar gains. (La Roche 2009, 2010).

Simple equations are derived from the experimental work to calculate internal maximum temperatures as a function of outdoor maximum temperature, daily swing, and glazing-to-floor ratio. One of these equations is tested in a real-size building with acceptable results on cloudy days. More series should be performed under different climates and with different types of buildings to determine the applicability of insulated and uninsulated green roofs and the effect of volume, thermal lag, thermal capacity, and other building variables. Until these series are performed, an applicability range similar to that indicated for thermal mass and night ventilation in Givoni and Milne's chart is proposed (Figure 9.17). In climates with moderate heating needs, where heat loss by conduction is not a critical issue, the uninsulated green roof could probably also be combined with a passive solar heating system (direct or indirect). The lower temperature limit of the climate zone that can be cooled by a night-ventilated green roof is a line slightly above the balance point temperature of a building, and the upper limit is determined by the upper limit of the night vented zone with thermal mass. More soil provides more thermal mass, which would affect the upper and lower limits. Caution must be taken in implementing the uninsulated green roofs because even if they do provide benefits when combined with night ventilation in some climates as indicated in Figure 9.17, the losses or gains during other periods can be larger than the benefits provided by the night ventilation cooling. However, in climates in which most of the points are inside the applicability area, green roofs, when combined with night ventilation, can lead to more comfortable conditions inside buildings and to increased energy efficiency. This should give them added value, thus increasing their applicability.

To increase the applicability of green roofs for cooling over summer and winter conditions, further research studied their energy saving potential adopting a variable insulation strategy (La Roche and Berardi 2014). A system consisting of a plenum located between a green roof and the space below it and a sensor-operated fan that couples (or decouples) the green roof mass with the indoor environment was developed. The fan is activated and stopped using temperature-based

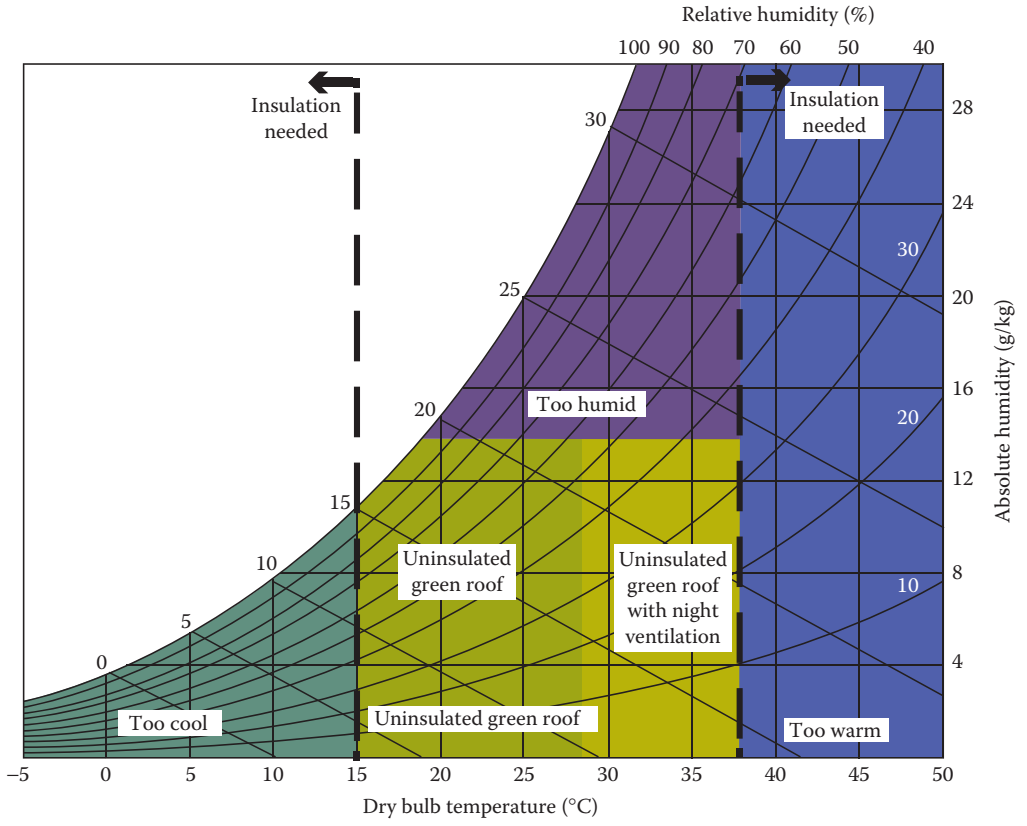


FIGURE 9.17 Applicability of night-ventilated uninsulated green roofs.

rules tested in previous research (La Roche and Milne 2003); the plenum is ventilated only when the fan works, thereby creating a variable insulation system. Four cells with an insulated traditional roof, a noninsulated green roof, an insulated green roof, and a green roof with the variable insulation system were tested in Southern California in a hot and dry climate with mild winters over several years. Research compared different plenum control algorithms, and results demonstrated that the variable insulating system adjusted the thermal capacity of the roof as required. In summer, the noninsulated green roof and the green roof with variable insulation system achieved the lowest indoor temperature combining the effects of night ventilation with the thermal mass of the green roof; in winter, the insulated traditional roof and the variable insulation green roof system achieved the highest indoor temperatures. Since the green roof was used as thermal mass combined with night ventilation, buildings with noninsulated and variable insulation night ventilated green roofs should work well when buildings with high mass and night ventilation are beneficial similar to the zone in Figure 9.17.

9.4 AMBIENT AIR AS A HEAT SINK (LATENT COMPONENT: EVAPORATIVE COOLING)

In the broadest sense, the term *evaporative cooling* applies to all processes in which the sensible heat in an air stream is exchanged for the latent heat of water droplets or wetted surfaces. Evaporative cooling uses the local atmosphere as a heat rejection resource. The amount of heat absorbed in the process of water evaporation (its latent heat) is very high compared with the other modes of heat transfer, which are common in buildings. This process is adiabatic, which means that no energy is

gained or lost. The sensible temperature is reduced with a gain in humidity. When moisture is added to the air, its absolute humidity increases while dry-bulb air temperature decreases. The evaporation of water is the basis of passive cooling systems such as the mechanical evaporative cooler, and on a psychrometric chart, this pattern follows the wet-bulb line upward to the left. There are several systems to produce evaporative cooling, and they usually involve a tower to produce the necessary height to evaporate the water and produce cool air or a pond. In hot and dry climates, evaporative cooling also increases thermal comfort because it brings the DBT closer to the comfort zone. In warm and humid climates, the increase in RH is not beneficial because conditions are then usually even more uncomfortable.

The heat loss potential of evaporation of the water is affected by the atmospheric pressure and the quantity of water vapor already in the air. At a standard barometric condition of 29.92 inch mercury (760 mmHg), water boils at 212°F (100°C) with a latent heat of vaporization of 1,044 Btu/lb (2.255 kJ/kg). Thus, if evaporation of 1 lb of water requires about 970 Btu (1,050 Btu at 76°F) and 12 lb of water evaporated in 1 h is equivalent to 1 ton of refrigeration or 12,000 Btu/h, then 1 lb of water will cover a 1 ft^2 pool to a depth of approximately 3/16 inch. In hot, dry climates, rates of evaporation of about 1 inch a day can be predicted; thus, a 1 ft^2 open pond can evaporate 5.2 lb of water per day, which produces cooling of about 5,460 Btu/day or 229.5 Btu/h ft^2.

An evaporative air cooling system is direct when the air stream comes in contact with liquid water or indirect when the air is cooled without addition of moisture by passing through a heat exchanger, which uses a secondary stream of air or water that has been evaporatively cooled.

9.4.1 Direct Evaporative Cooling

In a direct evaporative cooling system, the air is cooled by evaporation of water, and then the humidified and cooled air is introduced into the building to cool the space. When water evaporates within a stream of ambient air without supply of external heat, the temperature of the air is lowered and its moisture content is elevated while its wet-bulb temperature (WBT) remains constant (refer to Figure 3.8), providing adiabatic cooling. If the temperature as it lowers reaches the saturation curve, condensation will start at the dew point temperature (Figure 9.18, Point B). As the air loses water (Figure 9.18, Points B to C), the air is dehumidified by cooling in an amount that can be determined in the absolute humidity scale.

According to Givoni (1994), direct evaporative cooling can be applied only when the WBT of the ambient air does not rise above about 22°C (72°F), and indirect evaporative cooling can be applied to a WBT of about 24°C. The applicability of direct and indirect evaporative cooling is indicated in Figure 9.19. Direct evaporative cooling is not applicable for air with elevated water vapor content as in hot and humid regions. Direct evaporative cooling systems do not need to be complicated; the use of wetted pads close to windows or water surfaces like fountains are good examples of direct evaporative coolers.

Even though evaporative cooling towers can be used for both direct and indirect evaporative cooling, they are discussed in the section on direct evaporative cooling, and roof ponds are discussed in the section on indirect evaporative cooling.

Cool towers usually have wetted pads at the top or "showers." Cunningham and Thompson (1986) developed a downdraft tower with cellulose pads in the four faces at the top to which water is sent to maintain humidity (Figure 9.20). The hot dry air that enters the top of the tower and passes through the pads, cools, becomes denser, and drops to the base of the tower. The base of the tower is connected to the inside of the space and thus cools it. Excess water is collected at the bottom and recirculated with a pump. Cunningham and Thompson's (1986) system had a very good performance and achieved exit temperatures of 23.9°C with outdoor temperatures of 40.6°C and WBT of 21.6°C, demonstrating the power of cool towers in hot and dry climates. Givoni (1994) took two days of

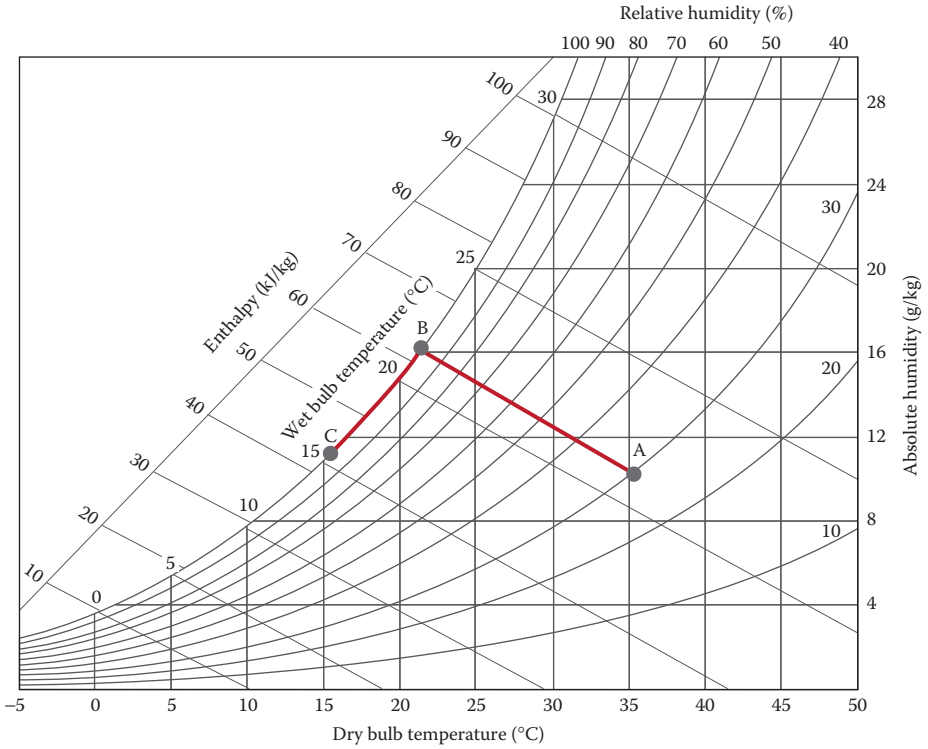


FIGURE 9.18 Adiabatic cooling and condensation.

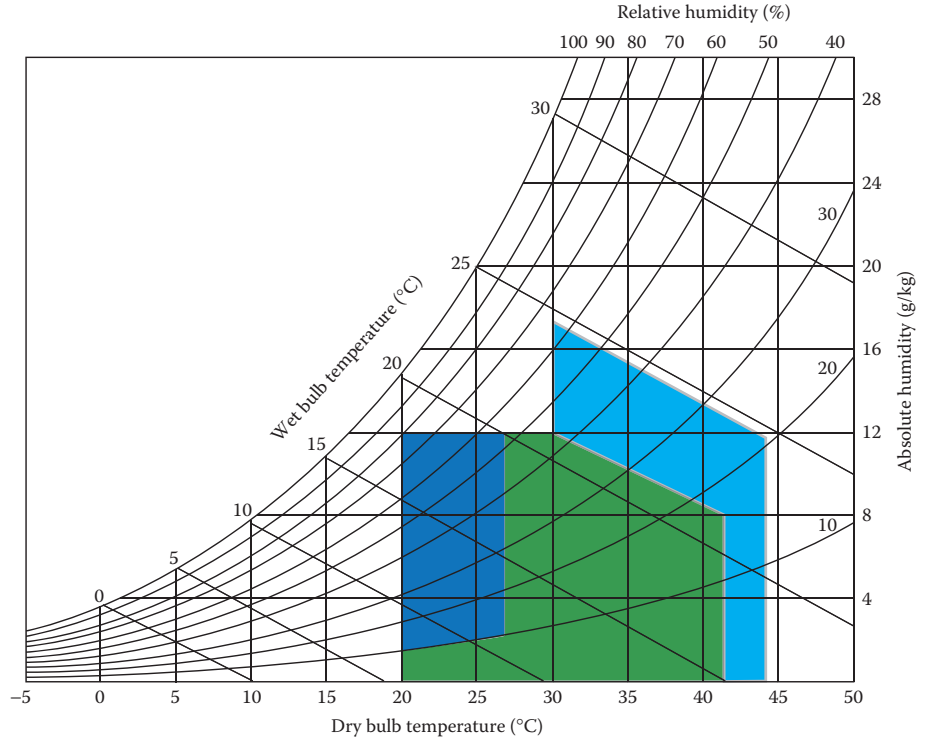


FIGURE 9.19 Applicability of direct and indirect evaporative cooling.

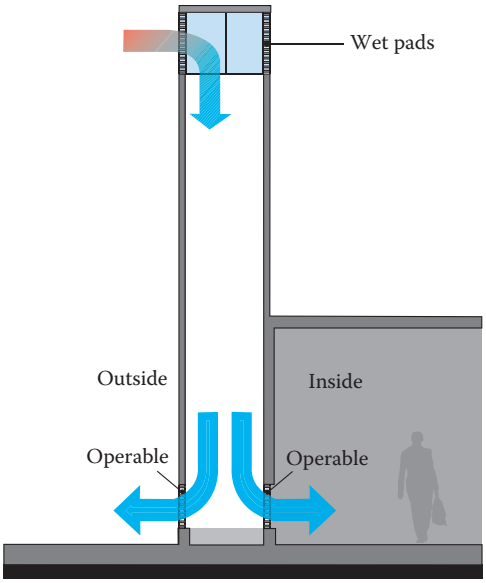


FIGURE 9.20 Cool shower with wetted pad.

experimental data from their work and developed a formula to calculate the temperature of the air exiting the tower:

$$T_{exit} = \text{DBT} - 0.87 \times (\text{DBT} - \text{WBT}) \tag{9.2}$$

where:

T_{exit} is the temperature of the air exiting the tower (°C)
DBT is the dry-bulb temperature of the air outside (°C)
WBT is the wet-bulb temperature of the air outside (°C)

This equation does not consider the wind speed. Because there is close agreement between the measured and computed temperatures, it seems that wind speed has only a minor effect on the performance of the tower, making this formula especially useful when wind speed data for the local site is not available.

Givoni (1994) proposes another equation to determine the flow rate and the exit air speed as a function of the area of the cooling pads, the tower height, and the WBT depression:

$$\text{Flow} = 0.033 \times A_{evap} \times \text{sqrt}(H \times (\text{DBT} - \text{WBT})) \tag{9.3}$$

$$\text{Speed} = \frac{\text{flow}}{A_{tower}} \tag{9.4}$$

Flow is the flow rate of air through the tower (m^3/s)
Speed is the exit air speed (m/s)
A_{evap} is the area of the wetted pads (m^2)
A_{tower} is the cross area of the tower (m^2)
H is the height of the tower (m)
0.033 is the constant representing the total pressure drop through the whole system that includes the cooling tower and the building

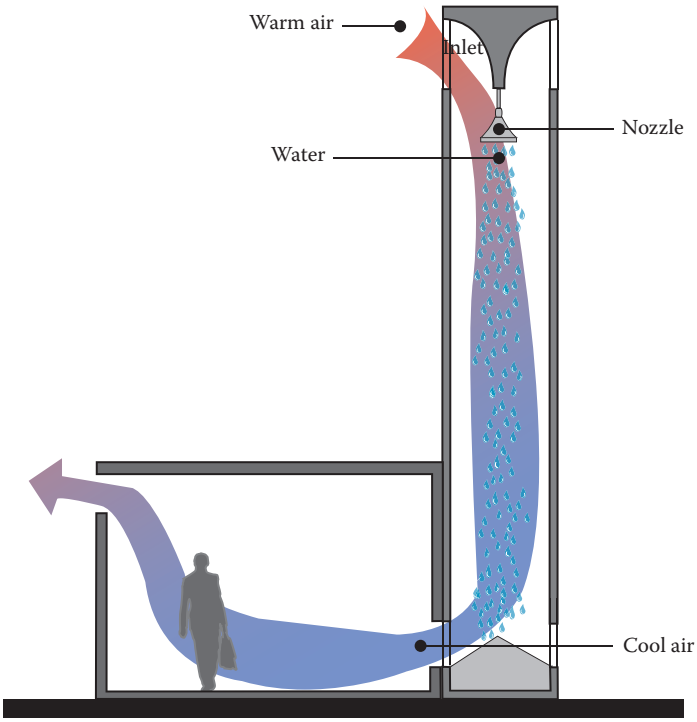


FIGURE 9.21 Direct evaporative cooling with shower.

This constant changes if the configuration changes. This can happen directly by conduction through the walls or indirectly through the use of heat exchangers that cool the air that penetrates into the building.

Givoni originally developed a cooling tower based on a shower instead of wetted pads for the 1992 World Expo in Seville, Spain. In this type of tower there are nozzles toward the top of the tower that spray very fine drops of water downward. As these drops fall, they bring with them a large volume of air, which is cooled by evaporation of the water drops, as well as the water to a level close to the air's WBT. The water is collected at the bottom of the tower and then pumped upward. A wind scoop can be placed above the showerhead to increase the airflow as it goes down (Figure 9.21). Theoretically almost any type of water can be used in these systems; however, there have been some problems with nozzle clogging with hard water.

9.4.2 Indirect Evaporative Cooling

Evaporative cooling can also be passive and indirect, when the system cools a given element of the building, such as the roof or a wall and this cooled element, serving as the heat sink of the building absorbing through its interior surface, the heat inside the building. This heat is transferred to the water in a pond or a shower where the water is cooled by evaporation. Thus, the heat from the interior of the building is transferred to the exterior of the space. The advantage of this system is that the interior space is cooled without elevation of the humidity, thus maintaining thermal comfort in more humid climates. Figure 9.22 shows a diagram of an indirect evaporative cooling system with a shower, and Figure 9.23 shows an indirect evaporative cooling system built at UCLA by Sukanya Nutalaya. There, water from the building is transferred in a closed loop and is transferred to the water in the shower via a heat exchanger (Figure 9.22). Because the indoor temperature is not elevated by indirect evaporative cooling and indoor air speed can be augmented by internal fans, the

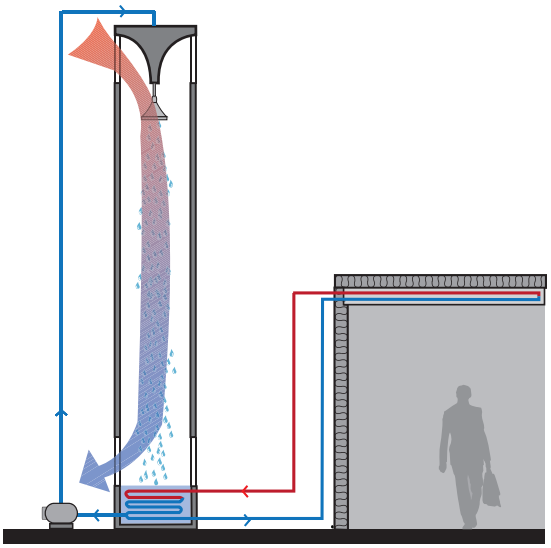


FIGURE 9.22 Indirect evaporative cooling with shower.

FIGURE 9.23 UCLA indirect evaporative cooling with shower.

limit for indirect evaporative cooling is about 2°C higher than the upper limit for direct evaporative cooling (Figure 9.19).

Examples of indirect evaporative cooling systems include installing shaded water ponds above uninsulated roofs or simply sprinkling water on the external surface of a roof. In the case of ponds, the surface temperature of the roof follows closely the ambient WBT, while the ceiling, which is thermally coupled to the pond, acts as a radiant or convective cooling panel for the space under it. In a roof pond system, the roof can be cooled by radiation, water evaporation on its surface, or both, and the indoor space is cooled by conduction of heat from the inside to the cooler outside. During the daytime, the roof pond is covered and shaded to block solar radiation and to reduce heat gains from the outdoors while it absorbs energy from the inside of the building (Figure 9.24). Water is an efficient heat sink that can absorb 1,157 Wh of heat per m^3 of volume and degree rise in temperature. If the water is enclosed in containers, it simply works as a heat sink for the space underneath.

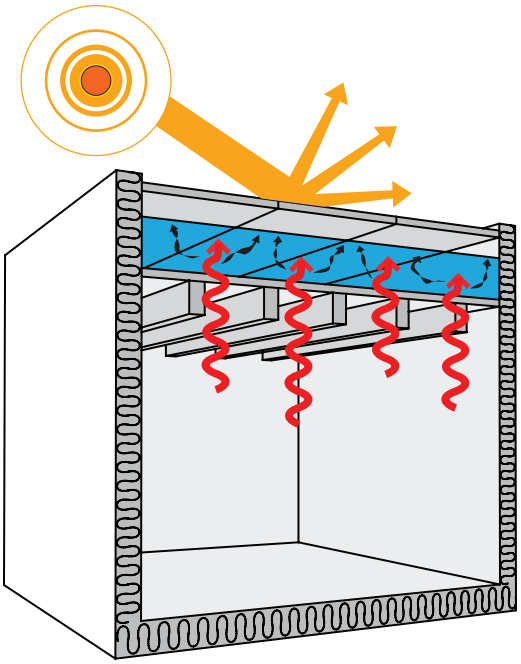


FIGURE 9.24 Roof pond daytime performance.

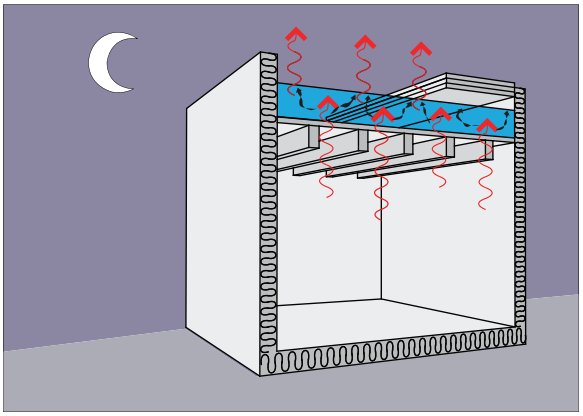


FIGURE 9.25 Roof pond nighttime performance.

If the water is exposed, some cooling by evaporation can occur with loss of water. This evaporative cooling effect can be augmented by spraying of water by nozzles, which can be located under the shaded area. During the night, the insulation above the water is open so that the water containers cool by radiation to the night sky (Figure 9.25). A clear sky is needed to maximize the radiant loss. Evaporative cooling with the nozzles can also be implemented at night because even though the wet-bulb depression will be lower, there are no heat gains from the sun. A key feature of a roof pond is that there is no insulation between the water and the space; the insulation or the shading system is placed above the water. Many variations of roof ponds control evaporation and radiation in different forms (Table 9.2). Roof ponds can have fixed or operable shading or insulating covers, and the water can be enclosed in bags or containers. These bags can also be sprayed or flooded for additional evaporative cooling.

TABLE 9.2
Types of Roof Ponds

	External Protective Cover	
Water	**Fixed Cover**	**Operable Cover**
Water enclosed in containers	The cover is fixed at an angle that blocks solar radiation during the daytime and allows heat loss during the night. Example: La Roche Marnich Cal Poly Pomona (Marnich, Yamnitz, La Roche, and Carbonnier, 2010)	The roof is operable, closed at night and open during the day. The containers are heat sinks during the daytime and radiate the energy to the sky at night. The roof is open at night and closed during the day. Example: Skytherm System
Water enclosed in containers that are sprayed or flooded	The cover is fixed at an angle that blocks solar radiation during the daytime and allows heat loss during the night. Additional cooling can be provided by water sprays. Example: Camelback School, AZ (Yannas, Evyatar, and Molina, 2006)	The roof is operable, closed at night and open during the day. The water is enclosed in containers that cool by radiation at night and act as heat sinks during the day. Additional cooling can be provided by water sprays.
Open water	The cover is fixed at an angle that blocks solar radiation during the daytime and allows heat loss during the night. Nozzles underneath the cover provide additional cooling by evaporation. The cover can also be fixed and cover the water as in a floating insulation system, in which case the water is cooled by radiation and evaporation during the night. Examples: Givoni–La Roche UCLA University of California Los Angeles (La Roche and Givoni, 2000) La Roche Marnich Cal Poly Pomona (Marnich, Yamnitz, La Roche, and Carbonnier, 2010) Gonzalez Universidad de Zulia (Givoni 2011)	The roof is operable, closed at night and open during the day. The water cools by radiation at night and a heat sink during the day. Additional cooling can be provided by water sprays. Example: Operable louver system at Cal Poly Pomona (Marnich, Yamnitz, La Roche, and Carbonnier, 2010)

9.4.2.1 Givoni–La Roche Roof Pond at UCLA

La Roche and Givoni (2000) tested a roof pond system at the Energy Laboratory of the Department of Architecture and Urban Design at UCLA during summer 1999 (Figure 9.26). This roof pond works as an indirect evaporative system and consists of an insulated water tank, cooled at night, and a test cell with cooled water circulating in pipes embedded in its concrete roof.

The test cell is 1.25 m wide, 1.40 m high, and 2.55 m long. Its walls are built with plywood outside and fiberglass inside. The roof has 100 mm of concrete (tubing embedded) above a metal plate, with 2-inch external insulation. The cell is painted white and receives direct solar radiation all day. Inside the cell, 190 concrete blocks (190 mm × 90 mm × 55 mm) comprise the thermal mass of the cell.

The pond was built using four 3 ft × 9 ft (0.91 m × 2.74 m) metal frames connected with screws and L connections. The area of the pond is 81 ft^2 (9.52 m^2). Inside these frames are R11 (1.937 m^2K/W) 5-inch (127-mm)-thick insulation panels. Two insulating panels are also floating over the water, which is held inside the insulation by a heavy-duty plastic liner so that there are no leaks. The initial water level of the pond was 18 inches (0.455 m), for a volume of 121 ft^3 (11.2 m^3). There are two independent water systems in the La Roche and Givoni (2000) experiment. The first one is the cooling system for the test cell, which pumps water from the pond to the roof of the experimental chamber and can run either continuously or at selected hours of the day using a timer. The other system is activated at night, cooling the pond by pumping water out of the tank and spraying it over the insulation.

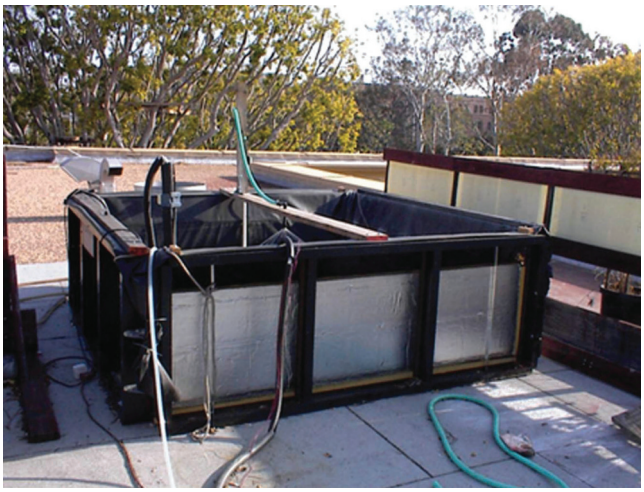


FIGURE 9.26 Roof pond system with floating insulation at UCLA.

Water circulates over the floating insulation panels at night, cooling by evaporation, convection, and radiation, and during the day these panels block solar gains to the water, keeping it cool. The pond is 6 m from the test cell, and the tubes that connect to the experimental chamber are 10 m long and are covered by insulation and aluminum foil to avoid overheating from the sun. The water circulates through this tube into the concrete roof of the cell, where it penetrates and cools from the inside, acting as a heat sink and absorbing heat from the building, keeping it cool during the daytime.

Several tests were performed and predictive equations were developed, but the equations demonstrated the direct relationship between the WBT and the performance of the system. One of the equations predicted the performance of the system as a function of the WBT and solar radiation after a 15-day cooling series.

The indoor average DBT was found to correlate best with the average WBT and the equation to determine maximum DBT inside the test chamber was

$$T_{mx} = \mathrm{WBT}_{avg} + \Delta t \tag{9.5}$$

where:

T_{mx} is the predicted maximum DBT inside the chamber on a particular day
Δt is the average elevation of the indoor maximum above the outdoor average
WBT_{avg} is the average WBT for the day

In this case, $\Delta t = 4.4$ K; however, this will change depending on the performance of the roof pond. Solar radiation can be included as another factor to determine the indoor temperature. Computed value where plotted with measured values and close agreement was found (Figure 9.27).

Another series of tests was performed in which the roof pond pump was not controlled by a timer but instead had sensors that operated a system according to relationships between the indoor and outdoor DBT. A datalogger was connected to several sensors that measured and compared temperature values. Rules were established that compared the temperature values in each of the sensors, and depending on the conditions, operated the pump by turning it either ON or OFF (Figures 9.28 and 9.29). New versions will operate the system comparing indoor temperature with outdoor WBT, which is a better indicator of pond performance.

Results from the tests with these roof ponds indicate that the indoor temperature in the cell without any cooling system activated (reference condition) is mostly a function of the outdoor average temperature; however, when the building is evaporatively cooled, the indoor temperature is mostly

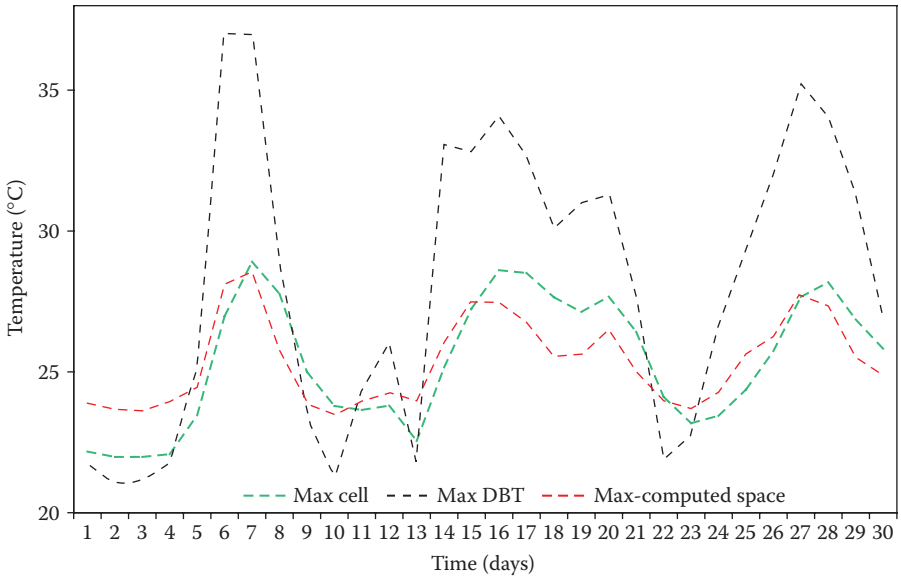


FIGURE 9.27 UCLA roof pond evaluated in a 30-day period.

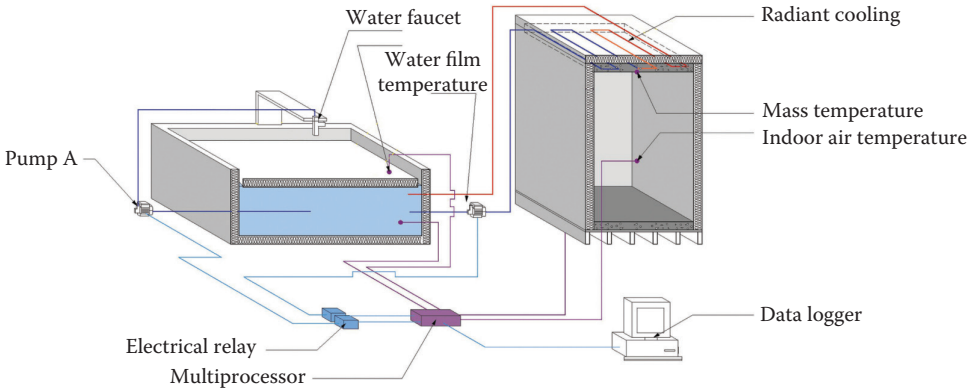


FIGURE 9.28 Roof pond system with floating insulation and smart controller at UCLA (summer daytime).

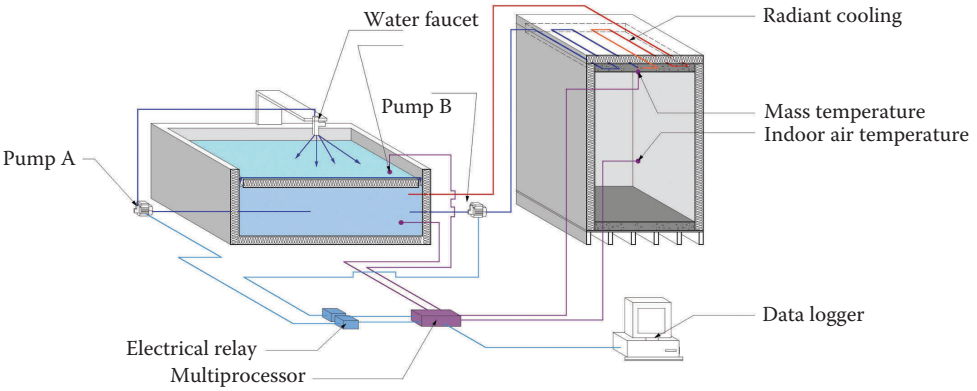


FIGURE 9.29 Roof pond system with floating insulation and smart controller at UCLA (summer nighttime).

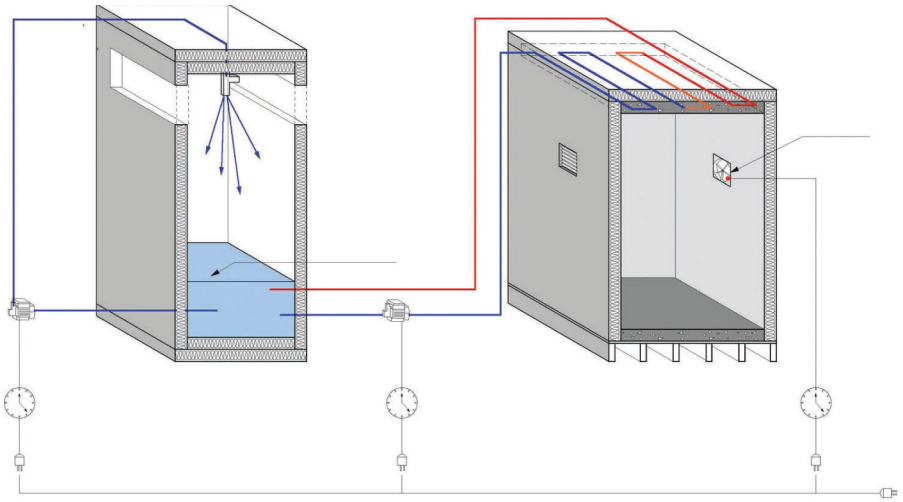


FIGURE 9.30 Diagram of shower system with indirect evaporative cooling.

a function of the outdoor average WBT, with the performance of the system improving with lower WBTs and higher WBT depressions. Even when night ventilation is combined with evaporative cooling, the dominant variable in the determination of air temperature inside the cell is the WBT (and higher WBT depressions). Other factors such as solar radiation and daily temperature swing were explored, but the WBT was always the dominant factor to determine evaporative cooling potential, making it easier to determine by knowing this single variable. These tests demonstrated that the pond, which is the main component of the cooling system, could be separate from the building.

Another indirect evaporative cooling system with a small shower that was only 2.40 m high was built (Figures 9.23 and 9.30). As with the roof pond, the indoor temperature was also a function of the outdoor WBT.

9.4.2.2 Roof Ponds in a Hot and Humid Climate

Even though roof ponds are traditionally implemented in hot and dry climates, they have also been successfully used by Kruger, Gonzalez, and Givoni (2010) in a hot and humid climate in Maracaibo, Venezuela. Maracaibo has year-round maximum average temperatures between 32°C and 34°C, with minimum RH between 50% and 60% and a small daily swing of about 5°C–6°C. Gonzalez et al. (2000) tested several configurations in test cells, including some in which a small pool of water was open to the air but was shaded. The drop of the indoor maximum compared with the outdoor maximum was about 3°C, or half the daily swing.

Gonzalez et al. (2000) then built a full-scale sustainable affordable house, also for Maracaibo. The roof pond in this house was shaded by a reflective horizontal plate, and air movement between the cover and the water was provided through screened pipes in the side walls and by small exhaust fans. Equations were developed by Kruger et al. (2010) to predict the indoor maximum, average, and minimum temperatures. When the spaces were occupied, the indoor maximum temperature was about 2.2°C below the outdoor maximum.

9.4.2.3 Cal Poly Pomona Smart Roof Pond with Floating Insulation

A roof pond with floating insulation in which the night circulation of the pond water is controlled by a smart controller was developed and tested at the Lyle Center for Regenerative Studies at Cal Poly Pomona (La Roche, 2006,2006c,2005b,2005c). Initially the pumps were controlled with a timer, but then a second set of series was performed in summer 2006, with a smart controller operating a pump connected to a

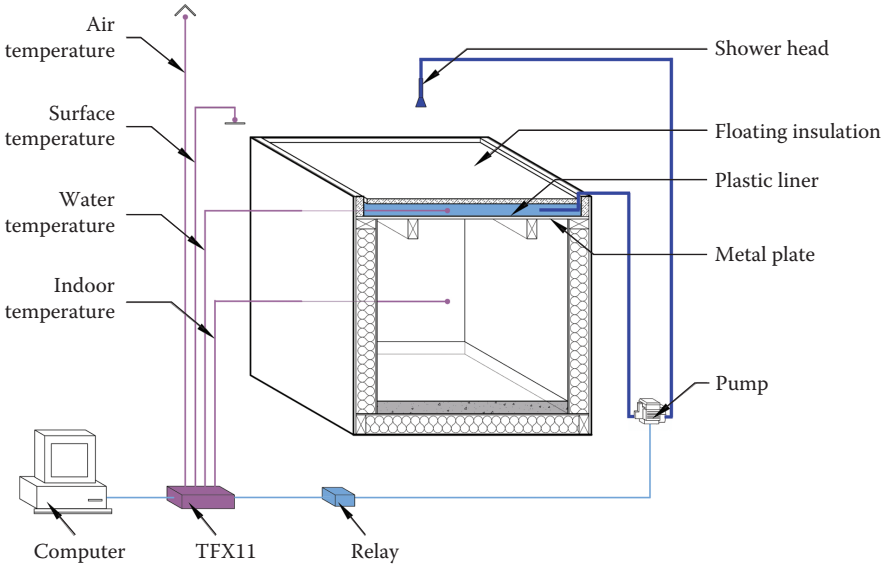


FIGURE 9.31 Smart roof pond at Cal Poly Pomona daytime.

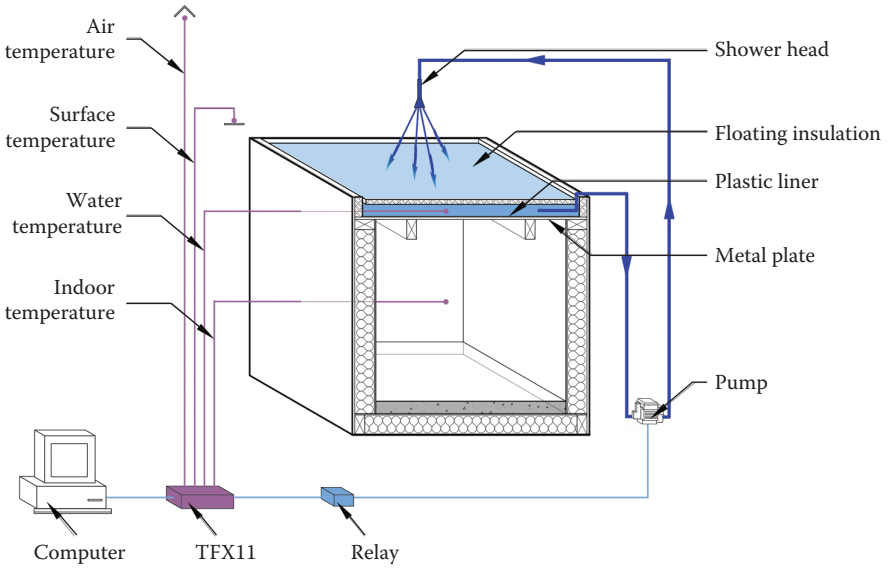


FIGURE 9.32 Smart roof pond at Cal Poly Pomona nighttime.

roof pond. Several cells were built that were 4 ft wide by 4 ft high with walls built with 2 × 4 studs and fiberglass insulation, plywood outside, and gypsum board on the inside. Both cells have a south-facing 2 ft × 2 ft window for a glazing-to-floor ratio of 25%. All the test cells were lightweight, without thermal mass. Shower head was at 0.75m,above the 0.5m height recommended by Yanas et al (2006).

Several rules were tested, and the simplest one compared the temperature of a metal painted black surface facing the sky with the air temperature. If the temperature of this surface was higher than the air temperature, then the pump would be OFF (Figure 9.31). If the temperature of this surface was lower than the air temperature, then the surface was radiating to the night sky and the pump was activated. This would happen at night (Figure 9.32). A more complex rule was

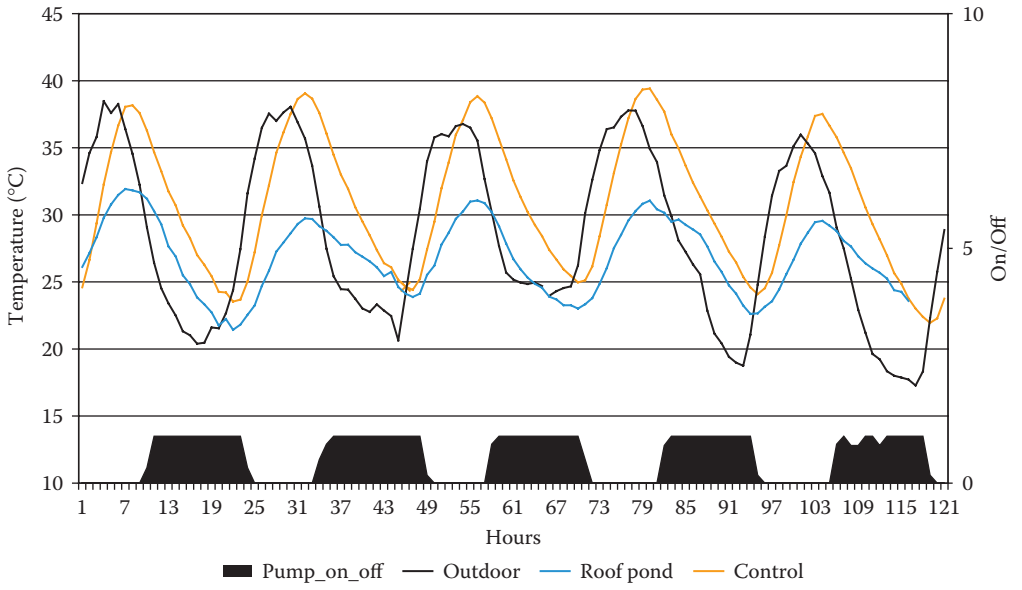


FIGURE 9.33 Indoor temperatures in the control and the cell cooled by the smart roof pond.

$$\text{If} \quad T_{\text{surf}}(A) < Outdoortemp(A) + 2 \text{ and } Roofpond(A) > Comfortlow$$
$$\text{and } T_{\text{water}}(A) > Lowatertemp \quad \text{then} \quad \text{PUMP ON} \tag{9.6}$$

where:

$T_{\text{surf}}(A)$ is the temperature of the external metal plate
Outdoortemp(*A*) is the outdoor DBT
Roofpond(*A*) is the temperature in the test cell with the roof pond
Comfortlow is the lower limit of the comfort zone
$T_{\text{water}}(A)$ is the temperature of the water
Lowatertemp is the lowest minimum temperature of the water

Figure 9.33 shows indoor temperatures in the control test cell (without any cooling) and the cell cooled by the smart roof pond, with the timing of the pump operation. The cell with the roof pond is always the coolest one, about 8°C below the control cell. These results demonstrate the effectiveness of the system and that indoor daytime temperatures can be much lower than the outdoors even in lightweight buildings.

9.4.2.4 Cal Poly Pomona Modular Roof Pond

Marnich, Yamnitz, La Roche, and Carbonnier (2010) developed and tested a modular roof pond system at Cal Poly Pomona. The purpose of this modular roof pond system was to develop a modular roof that could be installed with relative ease above any new or existing roof (that would support the load) without affecting the integrity of the structure. Another goal was that it would have a minimum of moving parts to reduce maintenance of the system so that it would be easier to adopt in many projects.

Two types of 4 ft × 4 ft modules were tested in different configurations to determine cooling potential. The two main types of configurations included one with bags full of water that cooled only by radiation and another with exposed water that had sprays of water that provided evaporative cooling. Both of these had fins that opened during the night and closed during the day. Some configurations had fixed fins in a position that blocked direct solar radiation during the daytime but permitted some

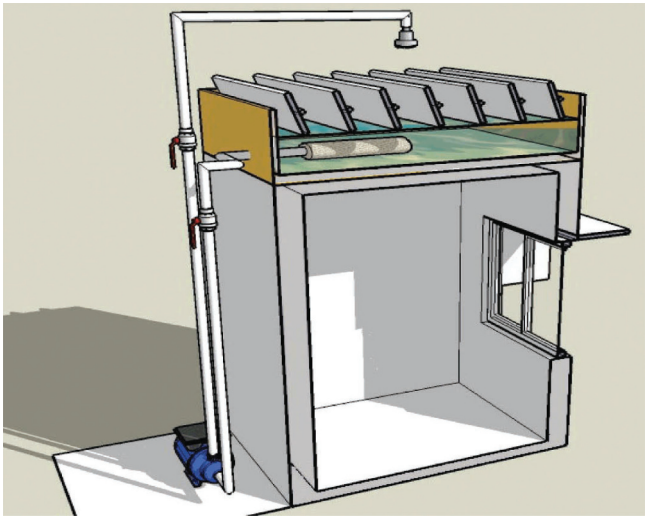


FIGURE 9.34 Operable louver roof pond at Cal Poly Pomona.

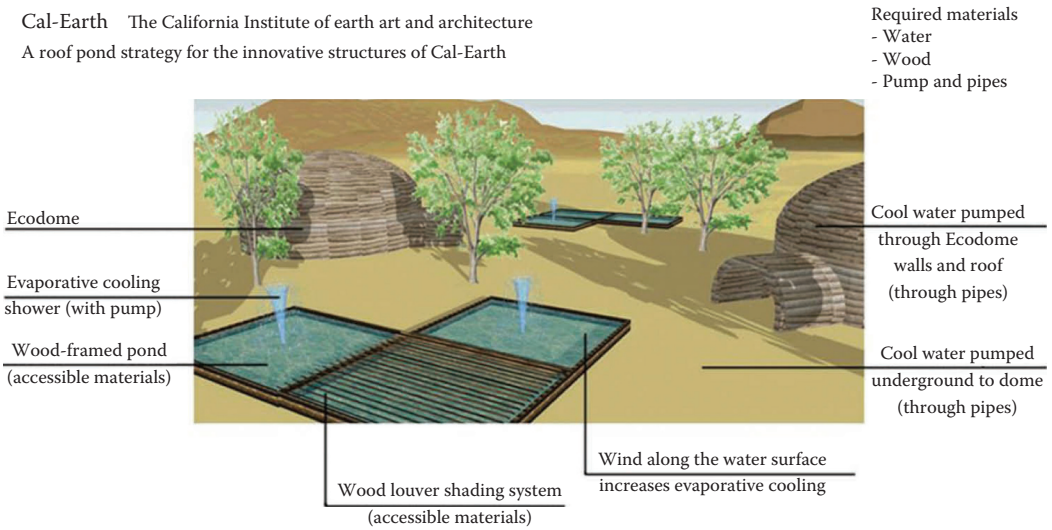


FIGURE 9.35 Evaporative system integrated with Cal Earth Ecodomes.

sky exposure during the night for radiant cooling. All types of roof ponds produced lower temperatures than the control cell, but the roof pond with the water sprayed horizontally at night across the pond below the shading panels cooled more than any other condition (Figure 9.34). The performance of these systems can further be improved, for example, by adding more intelligence to the controller and operating the nozzles and may be the fins of the roof pond at different times according to rules.

La Roche, along with several students, developed a roof pond with a system of operable louvers that work as a shading system and could be controlled by rules or a timer based on daytime or nighttime. If operating the louver system based on the time of day, it must be kept closed during the daytime and opened during the night (Figure 9.35). A sprinkler attached to a roof pond increases the amount of cooling by evaporation that takes place within a system. The students proposed to integrate these evaporative cooling systems with Cal Earth's Ecodomes, providing cooling in hot and dry climates (Figure 9.36).

9.4.2.5 University of Nevada, Las Vegas Roof Pond

Fernandez-Gonzalez and Hossain (2010) conducted promising research in the NEAT Lab at the University of Nevada, Las Vegas (UNLV) School of Architecture. Fernandez continued to test variations in the Harold Hays Skytherm System in two identical 2.69 m^2 test cells; one of which had a 22.9-cm-deep roof pond over its ceiling, which was made of corrugated metal deck. The walls were R16, and the standard automated garage doors provided the movable insulation for the roof pond. Both cells were shaded during the daytime with the garage door, and the cell with the roof pond had maximum average temperatures 6.6°C below the summer average maximum outdoor air temperature. If a spray of water was added, then the temperature could be lowered even more.

9.4.2.6 Fluid-Filled Windows

Research by Gullotti and La Roche (2015) tested a water-wall component system that increased thermal comfort through natural energy flows. The system utilized a design strategy similar to a Trombe wall, substituting the opaque thermal mass wall with a transparent water-wall. The thickness of the water-wall was designed for optimal visual clarity to the outdoors and optimal volumetric heat capacity. The water-wall used hydronic heat exchange to move water on demand to an isolated storage tank. A flat-plate collector acts as a secondary, isolated gain system for heating and cooling, storing heat during the day and releasing it at night (Figure 9.36). The component was tested at the Lyle Center for Regenerative studies and demonstrated a significant cooling potential.

Further research on fluid-based windows (Carbonnier, 2017) introduced a highly conductive gap medium inside windows using 10 nm Ø Al_2O_3 nanoparticles dispersed in deionized water to enhance thermal conductivity. The solution harnessed the photothermal properties of Al_2O_3 nanofluids to trap, store, and transport thermally charged fluids to heat exchangers to preheat air and water, and to generate electricity forming the Nanowindow—a transparent generator.

Seven Nanowindow prototypes with varying air and fluid columns were designed, fabricated, and coupled with three different heat exchangers and a thermoelectric generator. The iterative process investigated convection, radiation, conduction, and electric potential by comparing the Nanowindows to similar prototypes using distilled water. The experiments were conducted in a

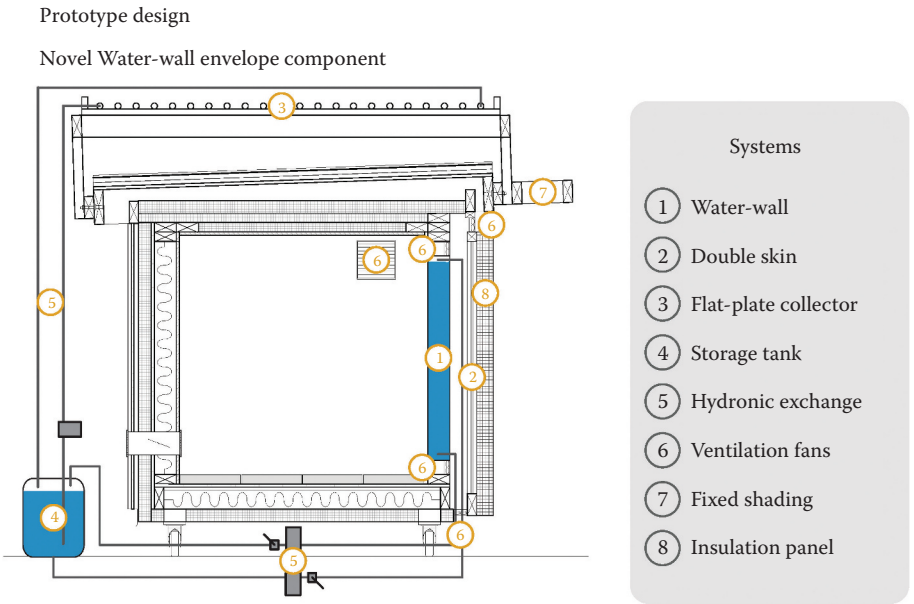


FIGURE 9.36 Water window system at Cal Poly Pomona.

custom-built solar lab composed of a low-cost solar simulator (LCSS) and calibrated hot box (CHB) providing standard test conditions (STCs) throughout the experiments.

The research confirmed that the optimal order of air and nanofluid (Al_2O_3) column favored the nanofluid proximal to the outdoor environment exhibiting U-Factor's ranging from 0.39 to 0.49, and solar heat gain coefficient (SHGC) of 0.43–0.670, which are comparable to double-pane window system and meet energy code requirements. In heat exchange experiments, Nanowindow's convective and radiative heat coefficient outperformed baseline water-filled windows by 8% and 22%. Using thermoelectric generators converted the 0.093 m^2 of Nanowindow to produce a rated voltage of 0.31VDC/0.075ADC at STC.

The potential for window gap technology to shift from resisting energy to harnessing solar energy presents a unique opportunity to turn windows into transparent generators.

9.5 THE UPPER ATMOSPHERE AS A HEAT SINK: RADIANT COOLING

9.5.1 Principles of Radiant Cooling System

Radiation is essential in maintaining the Earth's thermal balance. Outgoing radiation releases energy to outer space from the Earth and its atmosphere, and cosmic space is the ultimate absorber, balancing the energy inputs from the sun as well as from other sources. The sky provides the ultimate continuous heat sink to maintain the Earth's thermal equilibrium. It is the one passive cooling mechanism that parallels the only means of passive heating, the sun's incoming radiation.

All bodies radiate and absorb energy to the sky at the same time, and usually at different rates and wavelengths. Any ordinary surface that "sees" the sky and loses heat by the emission of longwave radiation toward the sky is regarded as a heat radiator. These radiant heat losses take place during day and night; however only at night, when there are no solar gains, the heat losses to the sky are higher than the heat gains (negative radiant gains) so that the building can actually be cooled. Starting at sunset, the exterior surfaces of buildings and the surrounding environment begin to be cooled by net thermal losses in radiation. However, the cooling power by sky radiation is quite small compared with the solar irradiation reaching the Earth. For example, in the southern United States, summer radiative cooling rates of 100–200 Btu/ft^2 (1,000–2,000 kJ/m^2) per night for a dry horizontal surface at 74°F (21°C) can be expected. This is similar to the radiant gains in 1 h daylight in the same location. Thus, a rule of thumb for a location with clear days and nights is that radiative cooling has a potential rate of about 10% of the summer radiative heating rate (Cook, 1989, p. 33).

One of the advantages of radiant cooling is that it has the least thermal impact on the immediate exterior environment. All that is needed is an exterior environment that does not impede the clear view of the sky: a roof facing the sky.

Five heat transfer processes affect the performance of any radiant cooling system (Givoni, 1994) as follows:

1. Longwave radiation emitted by the radiator; this is augmented by clear skies and reduced when overcast
2. Radiation emitted by the deep sky and absorbed by the radiating surface
3. Convective heat exchange between the radiator and the ambient air
4. Cold energy transfer from the radiator to the building, either by conduction or by forced airflow in the case of specialized lightweight metallic radiators
5. Convective heat exchange between the radiator and the heat transfer medium, the air (in the case of a lightweight radiator)

The system's performance depends in part on the climatic conditions and in part on the design details. The balance between the first two processes yields the net radiant heat loss, which is the climatic

potential for radiant cooling. The balance between the net radiant loss and the convective exchange with the ambient air yields the stagnation temperature of the radiator. The heat exchange between the radiator and the air flowing underneath and the airflow rate determine the temperature of the air exiting from the radiator and the cooling energy delivered to the building.

The intensity of longwave radiation emitted by a specialized radiator or by the roof itself when it serves as the radiating surface depends on only two factors: (1) the absolute temperature of the radiating surface (T_r) and (2) its emissivity (E_r) as defined in the Stefan–Boltzmann law:

$$R_e = S \times E_r \times T_r^4$$

where:

R_e is the intensity of longwave radiation emitted by a specialized radiator
S is the Stefan–Boltzmann constant 0.567×10^{-8} (W/m^2 K^4)

The emissivity of a radiating surface is a physical property that represents the potential of a surface to emit radiation relative to a perfect black surface. Most common construction materials, except metals, have emissivities close to 0.9. If a metallic material is the radiator, then it should be covered with paint, which usually has an emissivity close to 0.9. The paint layer then becomes the radiating surface.

The temperature of the radiator, and especially its relation to ambient air temperature, also affects the performance of the radiator. If the temperature of the radiator is higher than that of the air, then the radiator also loses heat by convection to the air.

The cloudiness of the sky affects the potential of heat losses to the upper atmosphere, because clouds emit radiation through the whole longwave spectrum. Under an overcast sky, radiant losses to the upper atmosphere are reduced, and the clouds literally block solar radiation losses to the sky.

One of the first recent radiant cooling systems was the Skytherm System developed by Harold Hay in 1978. In this system, the structural roof consists of a horizontal uninsulated metal deck, and thermal mass is provided by large plastic bags filled with water that are placed above the metal. Horizontal insulating panels, moved by a motor, insulate the water bags during the daytime and expose them to the sky at night, cooling the water bags by radiation. The metal ceiling serves as a radiant cooling panel for the space below. During the winter this process is reversed, and the system acts as a passive solar heating system in which the water is heated.

9.5.2 UCLA Radiant Cooling System

In developing countries, a large portion of the population lives in poverty, mostly in informal settlements with minimum access to basic living conditions. In these neighborhoods, most of the housing is generally built in stages using any available materials. A common initial stage of these dwellings is to have tin or zinc sheets for the walls and roofs (Figure 9.37) or brick walls with metal sheets directly above the walls. Usually the metal walls are replaced by brick walls as soon as the family has the financial resources to do this. These metal roofs, which are very common in many developing countries, are very hot during the daytime but cool down quickly in the evening as they radiate more energy to the night sky when they no longer receive heat from the sun.

In hot climates, DBTs during the day inside these dwellings are much higher than the outdoors, especially on sunny days, but values drop rapidly at nighttime until they are close to outdoor conditions.

In December 2000, data was recorded in a house with metal walls and roofs in Maracaibo, a city in Venezula, located in a hot and humid climate, at a latitude of 10.5 degrees north of the equator and at sea level. Even though it was cloudy during the days in which measurements were taken, indoor daytime temperatures were always much higher than outdoor temperatures. Two adults and three children live in the 40 m^2 house. Cooking is done inside the house, but dining and most of

FIGURE 9.37 House in an informal settlement in Venezuela.

the daytime activities are done outside under an *enramada*, which is a traditional covered outdoor space, usually in the back of the house and open to the backyard. While the porch faces the street and connects the house with the neighborhood, the enramada is for more private outdoor living.

Because of its proximity to the equator, daytime conditions inside the house would improve by adding insulation on the roof, but this would reduce the potential for radiant cooling during the night. Installing operable hinged interior insulation plates, even as simple aluminum foil, under the roof reduces daytime heating without interfering too much with the cooling effect of such roofs during the nights when the louvers would be open.

The effectiveness of storing the cold energy generated at the nocturnal radiant cooling for lowering the indoor air temperature during the daytime hours depends on the thermal storage of the interior space (Geros et al. 1999; Givoni, 1992). If mass is also present, as in the common brick walls, then it can be used as a heat sink during the daytime while the panels are closed to form an attic that acts as insulation.

The test cell used in this experiment was built at the Energy Lab in the roof of Department of Architecture at UCLA by Givoni, Gomez, and Gulish (1996). Its internal dimensions were 1.00 m × 1.00 m × 0.95 m, and the walls and floor were super-insulated with polyurethane panels 80 mm (3.5 inch) thick so that the radiant system is the main source of cooling. Many other series were conducted with different levels of insulation in the walls to further approximate typical buildings. The projected area of the gabled-sloped metal roof was 1.16 m × 1.60 m. The roof and the walls were painted white (Figure 9.38).

After painting the roof, it acted as a nocturnal radiator. Below it were located centrally hinged, lightweight, and operable reflecting panels. During the daytime the panels were in a horizontal position (closed), which formed a continuous insulation under the roof and thus reduced the heat flow into the interior space (Figure 9.39). During the night, the panels were turned into a vertical position, enabling radiant and convective heat flow from the interior space to the metal ceiling, which was cooled by longwave radiation to the sky (Figure 9.40).

The rotation of the insulating ceiling panels between the horizontal (closed) and vertical (open) positions was achieved by an electromechanical system designed and built by Gomez. Under computer control, the panels were opened at sunset and closed at sunrise, according to a prescribed action schedule calculated for the longitude and latitude of Los Angeles. In a real home, the panels could easily be controlled manually from the interior (e.g., by a rope). Interior operable insulation panels are not exposed to the wind and the rain, and thus can be simpler in construction, lighter, and much less expensive than external operable panels.

FIGURE 9.38 Smart operable radiant cooling system at UCLA.

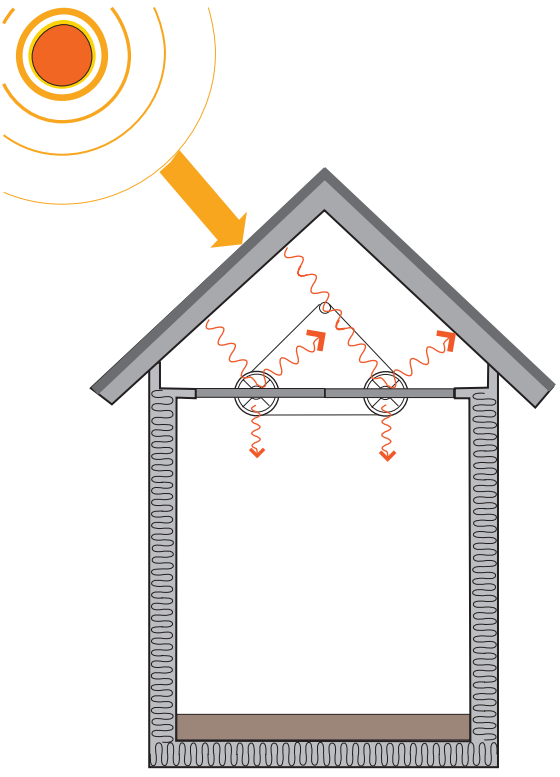


FIGURE 9.39 UCLA radiant cooling system during daytime.

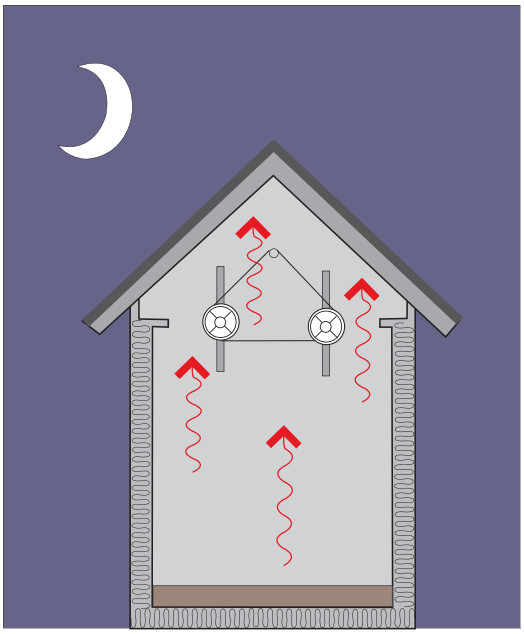


FIGURE 9.40 UCLA radiant cooling system during nighttime.

A series of experiments to determine the performance of the operable system with different combinations of mass were performed during several years between 2000 and 2002. Concrete bricks with dimensions of 89 mm × 57 mm × 190 mm were used as thermal mass. The positions of these bricks were changed in the different series from the floor of the cell to the walls, simulating the behavior of a building with a floor slab or brick walls. The distribution of the mass inside the space affected the temperature distribution and performance of the system. When the mass was located in the wall, the temperature was relatively uniformly distributed up to the height of the wall. On the contrary, when the mass was placed in the floor, most of the cool air stayed close to its surface, below a level in which it would be useful for occupants.

9.5.3 Zomeworks Double-Play System

Zomeworks has designed several radiant cooling and heating systems. *Double-play* is a system that uses overhead water storage as the working fluid for heat transfer and thermal mass. This system uses plain water as the heat transfer fluid and night sky radiation for cooling. The water circulates between tanks in the occupied rooms and absorber radiator arrays on the outside of the buildings. A solar thermal loop is used for passive heating. Results of testing over two years have been presented, and results are very promising (Beauchamp, 2010). In summer, the system removes heat from the building at a rate of about 4,875 Btu/h or 39,000 Btu in 8 hours, reducing the temperature of an 800 gallon tank 6°F. In winter, the system absorbs 52,000 Btu in a period of seven hours, raising the temperature of the same 800 gallons by 8°F.

9.6 THE EARTH AS A HEAT SINK: EARTH COUPLING

Ground cooling occurs when heat is dissipated from the building to the ground, which during the cooling period has a temperature lower than the ambient air temperature. This dissipation can be achieved by direct contact of an important part of the building envelope with the ground or by injecting air that has been circulated underground into the building, using earth-to-air heat exchangers.

The temperature of the Earth is relatively stable at depths between 6 m and 30 m. The long-term annual average is usually about 1°C above the mean annual air temperature and can be estimated by measuring the temperature of local well water. As we approach the surface, the Earth's temperatures track the air temperature more closely, and the ground surface temperature follows the sinusoidal pattern of solar heat flux. In a mild climate with cool winters, during the summer, the Earth's temperature below a depth of 2 m will probably be lower than ambient air, and the heat that a building gains from internal and solar gains can be transferred by conduction to the ground that surrounds it. If this ground temperature at a depth of 2–3 m is around or below 22°C, the soil acts as a heat sink for buildings. If the temperature of the Earth is above 22°C, then it is still possible to use the ground as a cooling surface by cooling the surface of the soil below its average temperature through shade that blocks solar radiation from the sun, and evaporative cooling at the soil's subsurface. The surface ground temperature amplitude is the maximum departure of temperature from the annual mean. If there were no other variables in play, it would increase, as solar radiation, with latitude.

Two additional considerations when designing an underground system are control of condensation and ventilation. It is also important to balance winter versus summer conditions. Summer losses would be beneficial; however, winter losses would not.

9.6.1 Ground Cooling of the Building by Direct Contact

A building exchanges heat with the environment by convection, radiation, and conduction. Conduction to the ground is usually through the slab. The conductive heat exchange between the building and the ground can be increased by maximizing the area of the building in contact with the ground (Figure 9.41). Conductive exchanges between the building and the ground must be augmented to increase heat losses from the building to the Earth; hence, it is not possible to use uninsulated walls in an earth-sheltered building located in a climate with cold winters because all of its

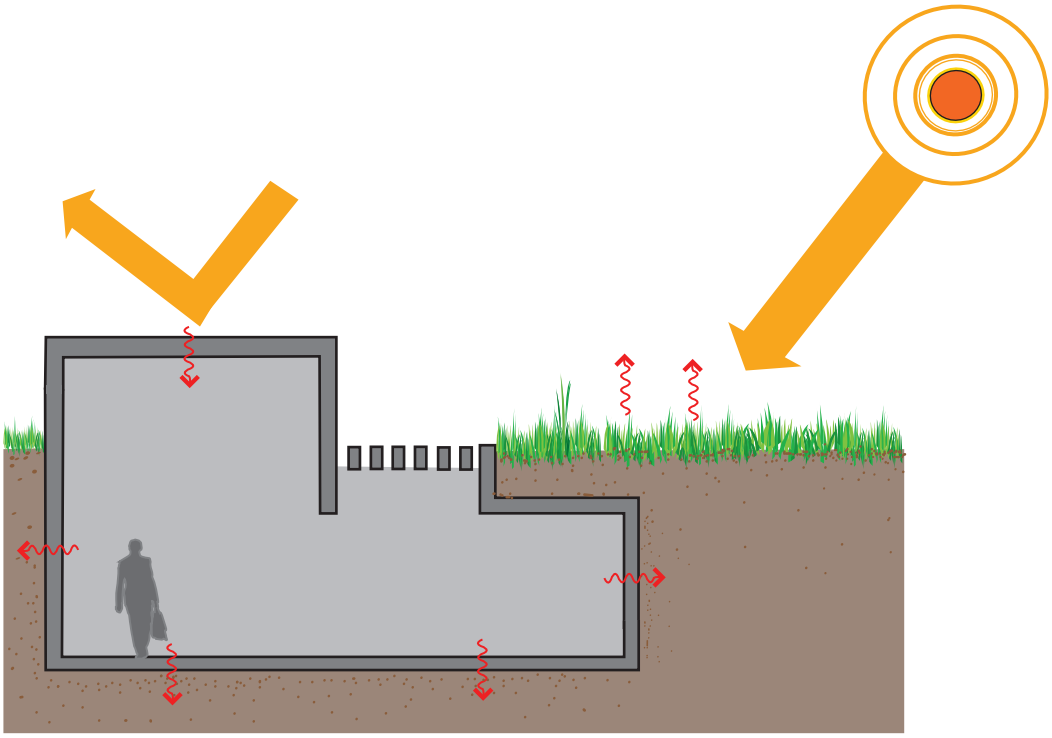


FIGURE 9.41 Cooling a building by direct earth contact.

heat will be lost to the Earth. If the building must be heated, then its walls should be insulated to avoid heat loss to the thermal mass around it.

Buildings can be earth-covered to varying degrees. A bermed structure is built on the surface grade with earth added around it and can be constructed below grade or into hillsides and be totally or partially covered by earth, including the walls and parts of the roof. As the surface of the building in contact with the thermal mass of the earth around it increases, its thermal inertia also increases, reducing temperature swings.

9.6.2 Ground Cooling of the Building by Earth-to-Air Heat Exchangers

If the building does not have enough surface in contact with the ground, then cooling can be supplemented by using earth-to-air heat exchangers, indirectly increasing the amount of earth in contact with the building. These exchangers are pipes, or *earth tubes*, which are buried horizontally at about 2 m deep, through which the air circulates by means of electric fans that suction it from the outside. As the air circulates through the outlet, it loses its heat to the earth around it, and during summer, when the ground temperature is lower than the outside air, the air temperature at the outlet will be lower than the temperature at the inlet. Because it is important to transfer heat between the pipe and the earth, the material should be conductive, and plastic, concrete, or metallic pipes are used. The temperature drop depends on the inlet temperature, the air velocity and volume of air through the pipe, the ground temperature at the depth of the heat exchanger, the thermal conductivity of the pipes, and the thermal diffusivity of the soil. Moisture in pipes can also lead to mold and mildew problems. Because of low heat capacity of the air and the relatively high temperatures and low air velocities that are obtained with earth tubes reducing their cooling potential, these are usually not competitive with mechanical air conditioning solely on an economic basis.

Earth tube systems are usually classified as open- or closed-loop systems. In an open-loop system, the air is drawn from the outdoors and delivered to the interior of the building, thus providing ventilation and cooling. The air that enters the building collects heat from the building and then exits to the atmosphere around it (Figure 9.42). In a closed-loop system, the air circulates through

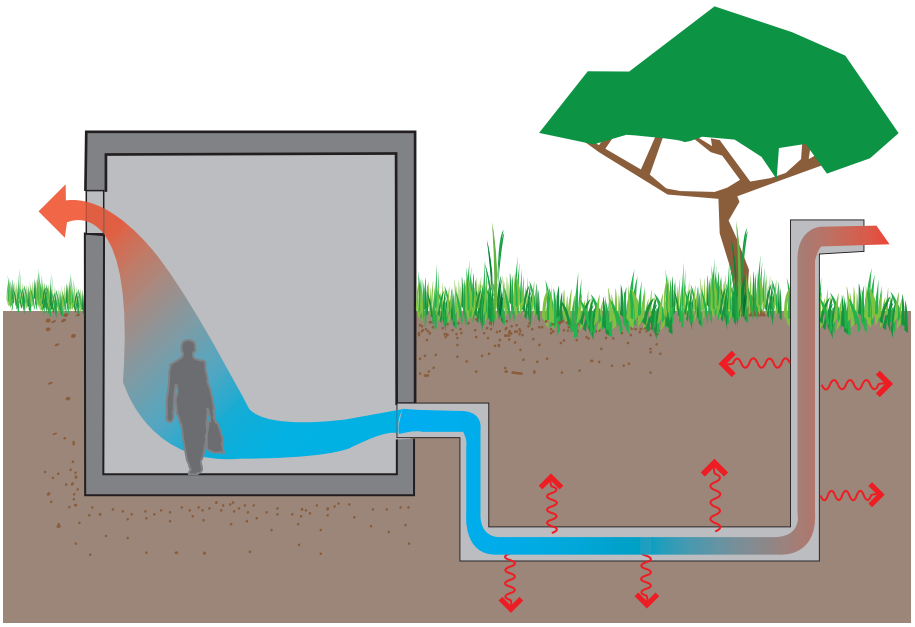


FIGURE 9.42 Cooling a building using open-loop air exchangers.

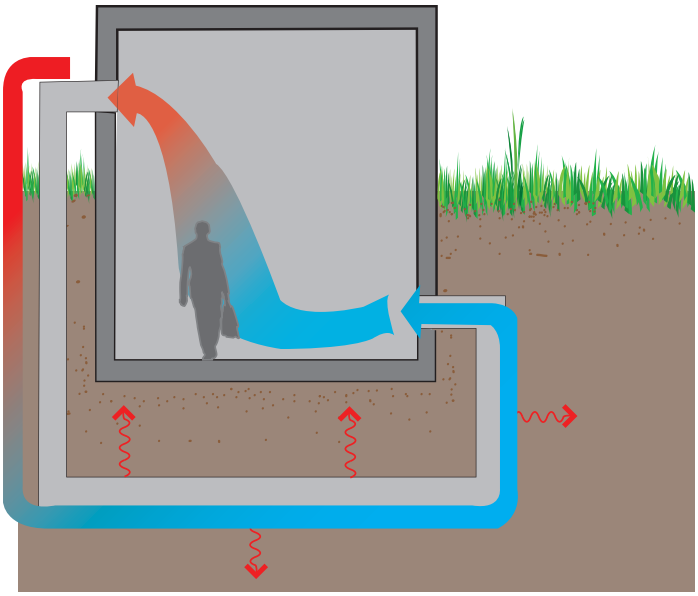


FIGURE 9.43 Cooling a building using closed-loop air exchangers.

the tubes and then back again. A typical closed-loop system would not connect the heat transfer fluid with the space; however, because air is used as the mechanism and it has such a low heat capacity, it is better to include the building space as part of the loop. The cool air enters the building from one side and exits through the other side to be cooled and reused again (Figure 9.43). Because this air coming out of the building might still be cooler and less humid than the outside air, a closed-loop system can be more efficient than an open-loop system.

It is usually assumed that earth tubes can provide sufficient cooling when ground temperatures are below 13°C. Because the Earth's temperature is about the same as the yearly average temperature, this will occur in mild-to-cold climates but not in a climate that is warm during the whole year, especially in a hot and humid climate in which average yearly DBTs are above 21°C. Even though the air can be cooled underground, it will not be cool or dry enough to provide sufficient cooling inside the space. However, a report by Sharan and Jadvah (2003) demonstrates successful use of earth cooling with pipes with average earth temperatures of 27°C and different comfort standards. With a soil temperature of 26.6°C and an air temperature of 40.8°C, an outlet temperature of 26.6°C was produced in a 50-m pipe that was 10 cm in diameter, 3 m below the surface, and with an air velocity of 11 m/s. This demonstrates how, because of its low heat capacity, the air temperature in the tube reaches the ground temperature quickly. Tubes need not be very long or very large in diameter; 20–30 cm is a recommended diameter. They should be placed at least 2 m below the ground; and if the soil has moisture or is cooled above ground, it will perform better. The tube should be conductive to transfer the energy from the air to the earth, so plastic or metal perform about the same.

9.6.3 Water-to-Air Heat Exchangers

A water-to-air heat exchanger (WAHE) can work as an earth-to-air heat exchanger but with more heat capacity. A series of experiments (Almodovar et al. 2016) tested WAHEs combined with indirect evaporative strategies in buildings with green roofs. The WAHE provides cooling while reducing

the energy consumption in buildings by using a water pond as a heat sink. Results show that a water container with a floating insulating panel and nighttime water spray has good potential as a heat sink for WAHE. The air flows from the test cell through the water, transferring heat from the cell to the water and then back to the cell as cooled air. The water spray above the insulating panel is turned on at night transferring the heat from the water to the air by evaporation and radiation. The spray is off during the daytime so that the water in the insulated pond does not receive external heat gains, only from the cell (Figures 9.44 and 9.45). Very promising results have been obtained with a 10.16 cm (4") diameter flexible aluminum pipe, which significantly increases air cooling and the amount of heat exchanged between the pipe and the water. The water tank, which was the same size as the experimental cells, was only heated around 3°C during the daytime. This means that the system presented in this paper would behave particularly well with a large water pond (a swimming pool, a fountain, a river or a lake). The heat from the interior of the cells that could not be absorbed by the green roof was transferred to the coupled water sink and then dissipated into the atmosphere. In particular, this study shows that the benefits of the WAHE and the evaporative cooling system are promising, although the water consumption is an issue to be considered. The system performed best when the underwater pipe length was longest, 3.5 m, keeping the indoor temperature of the experimental cell below 27°C during the daytime, while the ambient temperature was above 36°C, indicating.

The following conclusions emerged regarding the design of several variables:

Air velocity: An increase in the air velocity in the pipe provides more cool air into the test cell and increases the overall system efficiency. However, an increase beyond a certain value also leads to a reduction in the cooling through the pipe and consequently a higher returning air temperature of the air that enters the test cell from the pond

Pipe diameter: An increase in the pipe diameter increases the amount of cool air entering the cell and the system performance. The WAHE does not operate well with an underwater pipe that is 1.90 cm (¾") ¾" PVC, whereas better results were obtained with a 10.16 cm (4") diameter aluminum pipe.

Pipe length: As expected, the amount of heat exchanged between the water and the air increases with the length of the underwater pipe. However, good results were still obtained with a shorter 1.5 m long pipe. The measurements experimental data confirmed that the pipe diameter was more important than its length.

Pipe material: The higher the underwater pipe's thermal conductivity value, the greater the potential for cooling.

Research demonstrated the benefits of combining green roofs and evaporative and radiant cooling of the WAHE as a solution for building cooling.

9.6.4 Cooling the Earth

In temperate climates the earth mass under and around the building is a good cooling source for earth tubes, but in warmer climates the temperature of this mass might be too high. It is possible to use this mass of earth by reducing its temperature below that of the exposed soil. This can be done by either surface cooling or subsurface cooling (Figure 9.46).

Surface cooling is lowering the temperature of the soil surface and consequently the temperature of the earth's mass below the surface, providing a large amount of cooled mass. The simplest way to cool a surface is by shading to prevent the soil from being heated. This can easily lower the surface temperature by 8°C–10°C (14°F–18°F). Another strategy is to cover the soil with wood or a gravel mulching layer at least 10 cm thick that can be irrigated at certain hours. Solar radiation is absorbed and intercepted within the top 3 cm or 5 cm at the top of the layer, and the conduction of the heat down the layers of pebbles is rather low. The moisture from the irrigation is evaporated and the energy to do this comes mostly from the soil, lowering its temperature. Also, if the building is

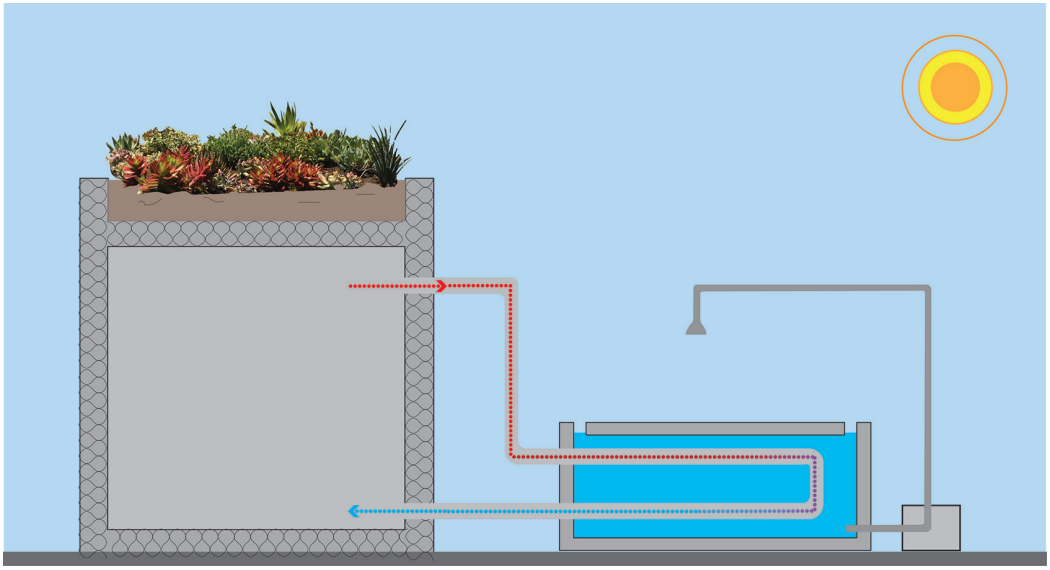


FIGURE 9.44 Water-to-air heat exchange with green roof during the day.

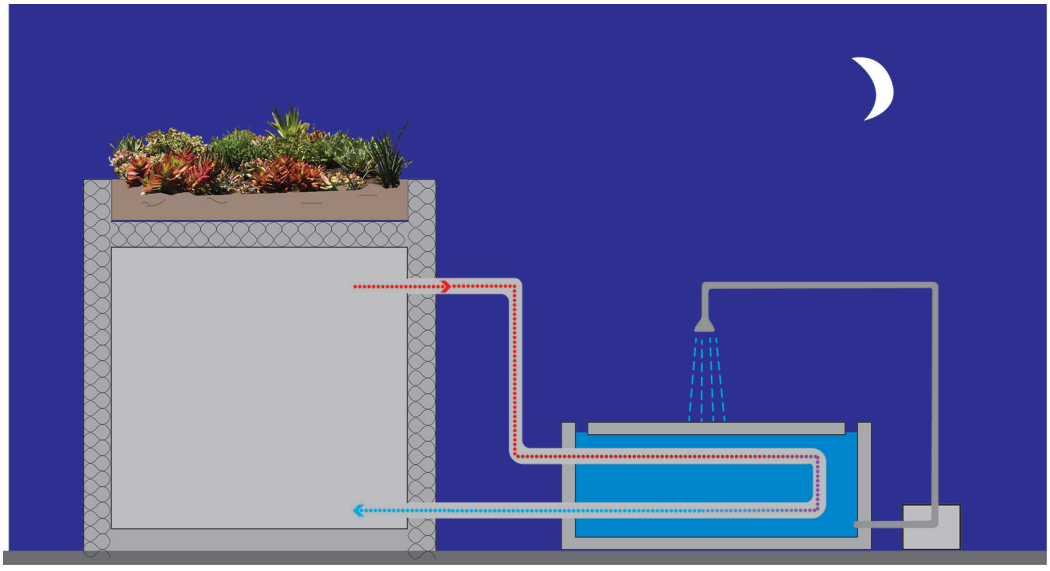


FIGURE 9.45 Water-to-air heat exchange with green roof during the night.

raised above the ground, the soil underneath can be humidified so that its evaporation will cool the air below the house (Figure 9.46).

Another cooling system tested by La Roche, Yeom and Almodovar (2016) investigated the cooling potential of a green roof paired with a radiant cooling system in a hot and dry environment in Southern California (Figure 9.47). The green roof had pipes embedded in it, which were connected to a radiator inside the test cell. The radiator absorbs heat from the interior of the cells which is dissipated through the green roof and the evaporative cooling that occurs during the irrigation process. Excess water that is not absorbed is recollected and reused. Experiments demonstrate the potential for a system such as this one that combines water-based cooling and green roofs, to improve thermal comfort and reduce energy consumption. The test cell with the

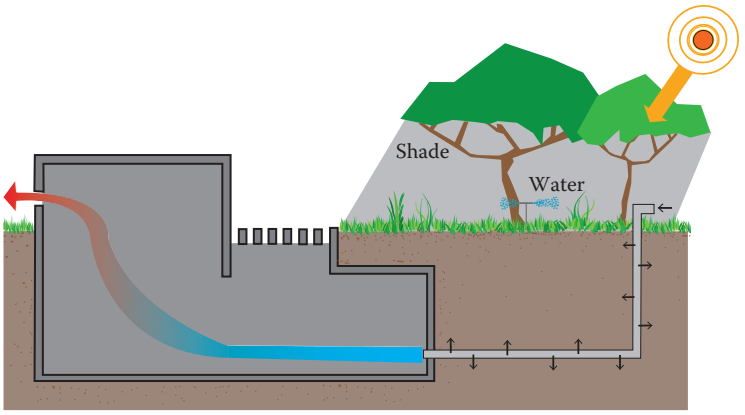


FIGURE 9.46 Cooling the earth around a building.

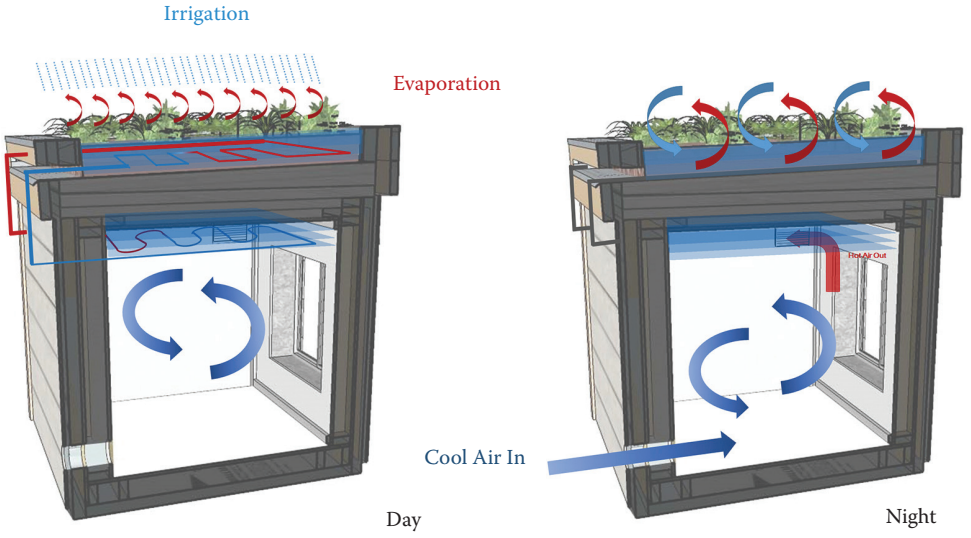


FIGURE 9.47 Radiant cooling system with the green roof.

green roof and radiant cooling system was monitored and compared with other cells in over 40 tests conducted over the summers of 2015 and 2016. The results demonstrated that this test cell maintained lower indoor temperatures than the other test cells, including other cells with green roofs. The best performance occurred when the radiant system pump was operating continuously, with the irrigation sprinkler working 20 minutes per hour from 11:30 a.m. to 4:30 p.m. The irrigation system cools the earth, which also cools the liquid in the radiant pipes. These cooled pipes cool the building, and reduce the heat island effect produced by roof surfaces.

9.7 APPLICABILITY OF PASSIVE COOLING SYSTEMS

The main features of passive cooling systems are presented in Table 9.3. This table includes the natural heat sink used to transfer the heat from the building, climatic applicability that describes outdoor conditions under which it would perform appropriately, physiological effect, and the dominant building element that will affect its performance.

TABLE 9.3
Passive Cooling Systems

Passive Cooling System	Heat Sink	Climatic Range	Physiological Effect	Dominant Building Element
Comfort ventilation	Air	Max temp < 30°C RH < 80% WBT < 24°C	Increases sweat evaporation from the skin. Cooling and convective heat loss from the body.	Large openings to promote air movement Low mass to avoid storing heat
Nocturnal ventilative cooling	Air	Large diurnal range >12°K Min DBT < 20°C Max DBT < 38°C RH Absolute humidity < 14 g/kg	Decreases MRT of interior walls	High mass with external insulation Windows should be operable to permit air exchanges at night but closing at day
Radiant cooling	Space or upper atmosphere	Clear nights Humidity and temperature are not as important	Reduces MRT of interior walls	Roof surface to the sky
Evaporative cooling: Direct and indirect	Air: Uses water as transport (direct) and heat sink (indirect)	WBT < 21°C DBT < 42°C WBT < 24°C DBT < 44°C	If RH is low, it can be raised increasing comfort. If RH is high, an indirect system would be better.	Roof design or tower. Could also be features in the landscape around a building
Earth coupling	Earth	Average yearly DBT < 13°C for earth tubing For direct coupling if climate is temperate, soil temperature below 2 m will probably be cooler than air temperature If outdoor temperature is hot, surface temperature above the ground can be cooled to reduce underground temperature	Reduces air temperature and increases comfort by increasing the effect of cooling sensation by radiation	Relationship to earth, either sideways, above or below

Note: RH: Relative Humidity; WBT: Wet Bulb Temperature; DBT: Dry Bulb Temperature; Min DBT: Minimum Dry Bulb Temperature; MaxDBT: Maximum Dry Bulb Temperature.

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10 Passive Heating

10.1 APPLICABILITY OF PASSIVE HEATING

In the psychrometric chart, if environmental conditions are to the left of the comfort zone, then the body loses more heat than it gains, and heat must be provided to achieve thermal comfort. Passive solar heating provides this heat to the body by warming the space around it. In general, conditions to the left of the comfort zone can benefit from passive solar heating, if there is enough solar radiation to provide the necessary energy and if the building has the appropriate design features to capture energy, thermal mass to store it, and insulation to keep the heat inside. When outdoor conditions are below but still relatively close to the comfort zone, thermal mass or internal gains are sufficient to achieve thermal comfort, and requirements are more lenient. But as the outdoor temperatures become lower, the building must be designed with more stringent requirements (e.g., better insulation, tighter and better windows, and additional thermal mass). It is generally assumed that the lowest outdoor temperatures with which we can provide sufficient heating to a building, using only passive solar strategies, is around 5°C (Figure 10.1). However, there are examples such as the Rocky Mountain Institute in which the building uses special glazing, super-insulation, and large amounts of thermal mass to achieve thermal comfort with outdoor temperatures well below 5°C.

10.2 CONTROL OF HEAT LOSS

In cold climates, a building will lose heat by conduction through its walls, roof, and floor; by convection (infiltration) through the window frames; and by radiation through sky-facing surfaces (Figure 10.2). The building can also gain heat by radiation when the sun is available, although this is not considered when sizing mechanical systems.

The first step to achieve thermal comfort inside a building in the winter is to reduce heat losses from the interior of the building to the colder exterior. These strategies were discussed in Chapter 5 and include the reduction in heat losses by conduction and infiltration. Losses by conduction can be reduced by improving the insulation of the building skin, creating a more compact building, and making a tighter envelope. Infiltration losses can occur through all the cracks in the building, including the bottom of the drywall, edges of the window, and even the plumbing and electrical fixture conduits. These can be reduced by including an air infiltration barrier system or moisture barrier, adding weather stripping, and using caulk to fill holes in siding or masonry or to seal the transition gap between two different types of finishes. Infiltration rate should not be reduced below a value that compromises the indoor quality of the space. Emissions from occupants (CO_2) and construction materials inside the building require air exchange with the outdoors to maintain appropriate indoor air quality. Reducing building heat losses by infiltration and conduction are not passive heating strategies, but they are necessary because they help to keep inside the building the heat provided by passive, active, or mechanical systems inside the building. This chapter introduces the most common passive strategies that can be used to heat a building.

10.3 PASSIVE SOLAR HEATING

The simplest method to passively heat a building is to increase solar gains to the interior of the building. Passive solar systems must have a medium to collect or capture solar gains, a medium to store this energy, a medium to distribute this energy, a well-insulated and well-sealed skin to keep

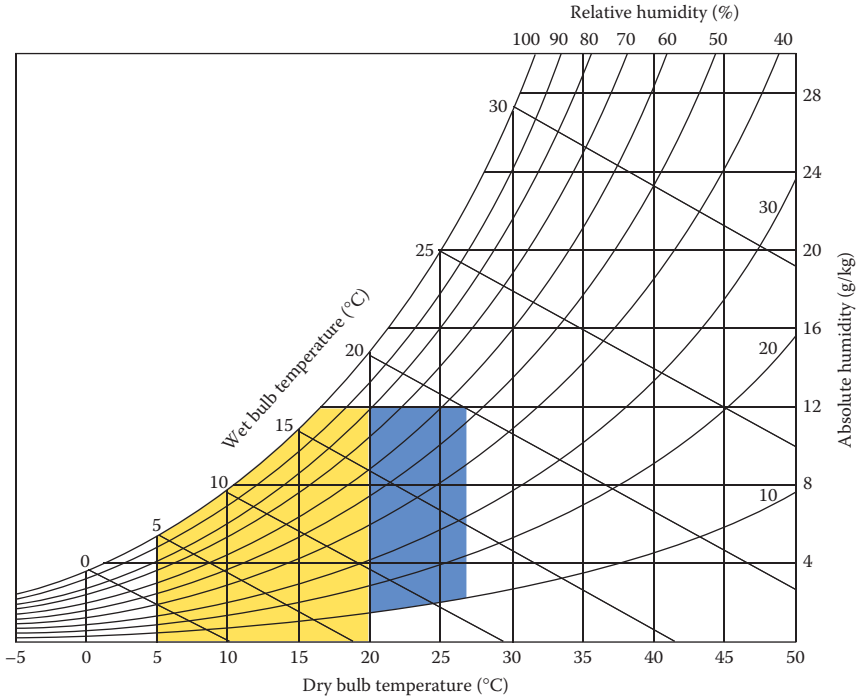

FIGURE 10.1 Outdoor conditions for which passive heating strategies will help achieve thermal comfort.

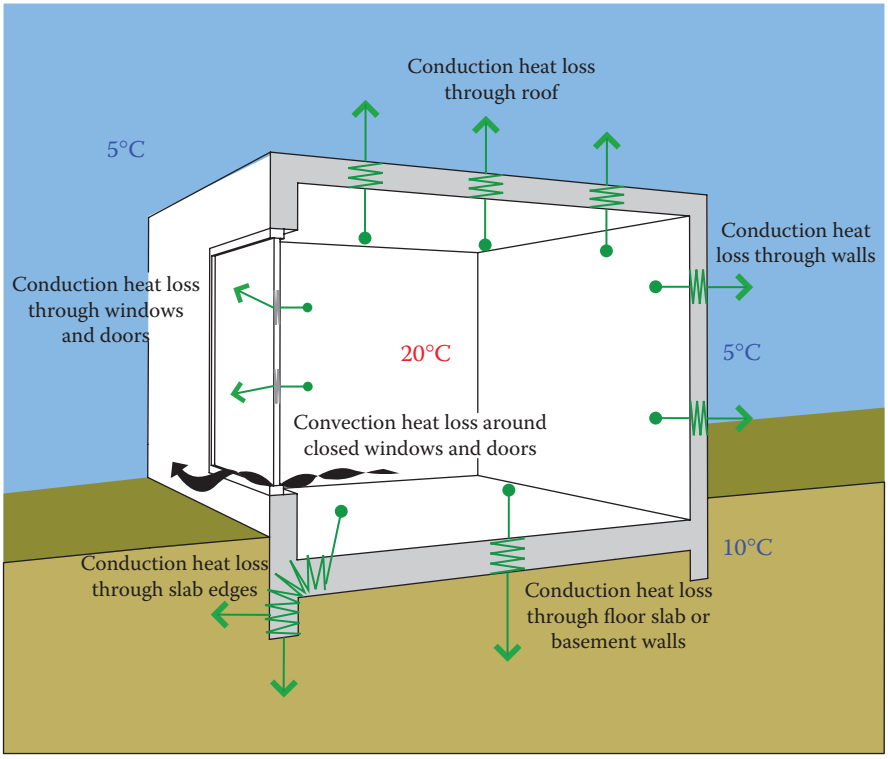

FIGURE 10.2 Heat flows through a building skin in the winter.

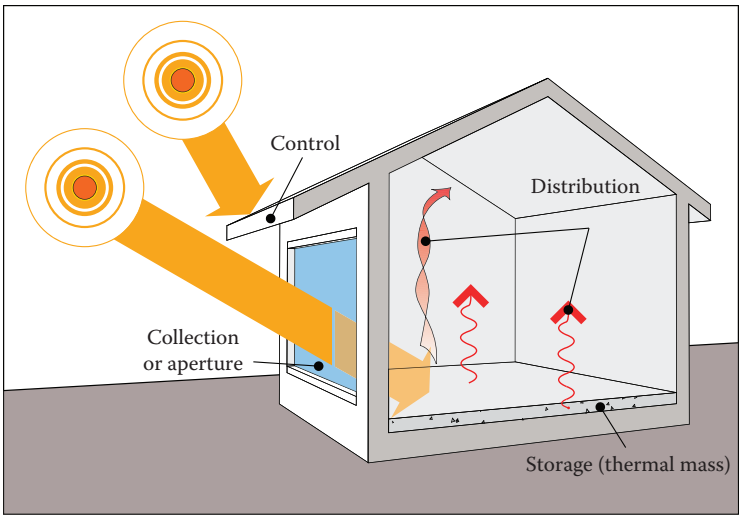

FIGURE 10.3 Components of a passive solar system.

this energy inside during the underheated period, and control elements to reduce heat gains in the overheated period (Figure 10.3).

A passive solar system will capture heat during the day coming from solar radiation and will store it for night use. To achieve this, it must have mass on the inside for thermal storage and insulation on the outside. The thermal mass must face the interior so that it can be heated from the inside and then emit this heat back to the occupants, and the insulation must be on the outside to keep the heat from the thermal mass inside during the night. When designing a passive solar system, it is important to match the time when the sun can provide solar radiation to heat the space with the amount of thermal mass needed to store and provide the heat when it is needed inside the building. In general, a passive heating system will raise the average temperature of the building above the average temperature of the exterior and will have a smaller swing (Figure 10.4).

As we move farther away from equatorial latitudes, the optimum orientation for passive solar buildings is with the collection surface facing toward the equator because this is the facade that receives more solar radiation in the winter months. As the latitude increases, it becomes more and more important to have the collector surfaces facing south. It is usually considered good practice to keep the collector's orientation within 15° of equatorial orientation with an unobstructed solar radiation window between 9 a.m. and 3 p.m. However, this varies as a function of specific microclimatic conditions such as morning or afternoon cloudiness. Generally, buildings oriented along an east–west axis provide

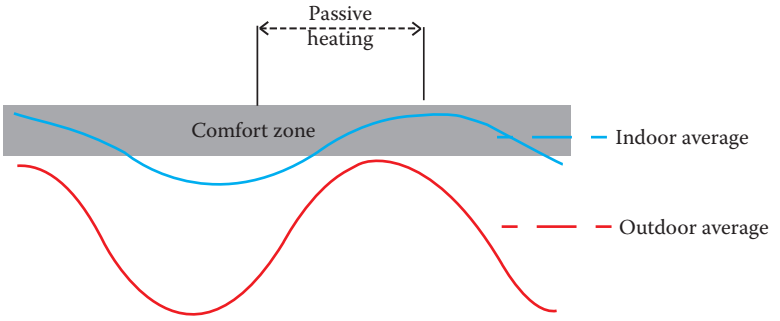

FIGURE 10.4 Effect of thermal mass and passive heating on indoor daily temperature swing.

more winter heating because they allow for maximum solar collection to the south during the whole day. This orientation is also advantageous during the summer because it minimizes east–west exposure, which is not helpful in the summer and is more difficult to control. Equatorial-facing collectors need not be all located along the same wall. For example, clerestory windows in buildings located in the northern hemisphere can project south sun deeper into the back of the building.

In an east–west-oriented building, a polar-facing exterior wall will receive no direct solar radiation during the winter and becomes major source of heat loss. Because windows have a much lower *U*-value than walls, window surfaces on north-facing walls in cold climates should be small to reduce heat losses. Additionally, building shading of open spaces to the north of the building usually render them unusable for outdoor use during the winter.

Habitable spaces that are occupied the most with the highest heating and lighting requirement should be arranged along the equatorial facade of the building. However, overheating and glare can occur whenever sunlight penetrates directly into a building, and their control must be addressed through proper design. Rooms that are used the least (e.g., in residential buildings, closets, storage areas, and garages) should be placed along the polar-facing wall where they can act as a buffer between high-use spaces and the exterior, which does not receive any radiation. An open floor plan optimizes passive system operation.

A passive solar building that uses solar radiation as a heating source should also be designed to take advantage of solar radiation as a lighting source. However, each of these has different design requirements that must be addressed. In general, passive solar heating requires direct solar radiation to strike a surface and heat it, whereas daylighting requires diffusion of this radiation over larger areas of light-colored surfaces.

10.4 TYPES OF PASSIVE HEATING SYSTEMS

Passive heating systems are usually classified in three main groups: direct gain, indirect gain, and isolated gain systems. Direct gain systems use the actual living space as the solar collector, heat absorber, and distribution system. Indirect gain systems have the thermal mass located between the sun and the living spaces, and isolated gain systems have their components separated from the main usable areas.

10.4.1 Direct Gain Systems

The simplest passive solar heating system is a direct gain system that is an insulated building with internal thermal mass and equatorial-facing windows. In a direct gain system, solar radiation enters the living space and hits the thermal storage mass where it is stored to be reemitted later at night (Figures 10.5 and 10.6). Thus, the living space where the mass has been stored is a “live-in” collector. A direct gain system uses 60%–75% of the solar energy striking the windows of the system.

The requirements for direct gain systems are a large amount of equatorial-facing glazing and exposed thermal mass in the floor, walls, or ceilings that are sized with enough capacity for thermal storage and positioned for solar exposure. The equatorial-facing glass admits solar energy into the house, where it falls on the thermal mass of the house. These materials store the energy during the daytime and reradiate it to the space sometime during the night after the space is no longer receiving any solar radiation. Double glazing is used to reduce the losses at night, and operable insulation in the form of blinds can be used to increase the insulation level of the windows and to reduce heat losses by conduction.

Direct gain systems have several advantages. First, they are very simple to conceptualize and build. It is possible to create a direct gain system by simply placing the windows in the right location, and because they are simple the whole system is also inexpensive. Second, the large areas of glazing admit not only solar radiation but also natural light and provide visual connections with the outside. And third, glazing is readily available, and even the simplest most inexpensive windows can provide a greenhouse effect.

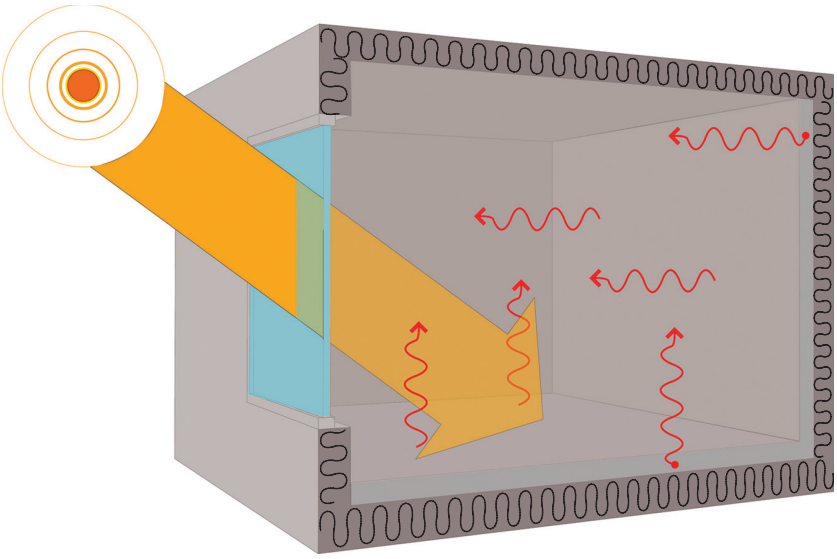

FIGURE 10.5 Direct gain system during the day.

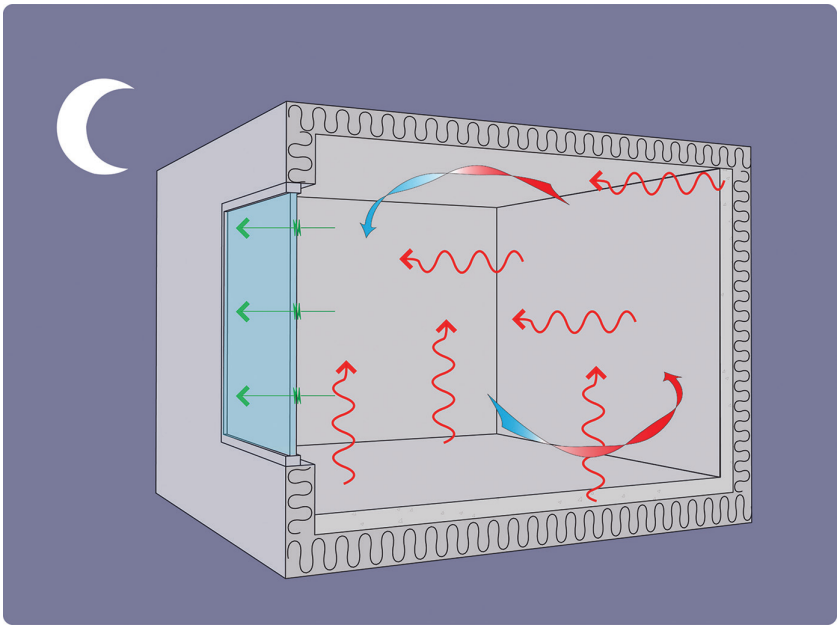

FIGURE 10.6 Direct gain system during the night.

Direct gain systems also have several disadvantages. The large areas of glazing can create glare during the day and loss of privacy at night. In addition, ultraviolet radiation from the sunlight can degrade fabrics and photographs. Also, large glazed surfaces and large amounts of mass are needed for the system to be effective, and this additional mass can be expensive if it does not serve any structural purpose. And even with mass, diurnal temperature swings of 10 K are common. Additional night time insulation in the windows is also needed at night when outdoor night temperatures are very low.

The three most important factors to consider in the design of a direct gain system are the amount and orientation of the glazing, the amount and distribution of the thermal mass including its thickness and position, and the insulation level of the envelope. The glazing area determines how much solar heat can be collected in the building, and the amount of thermal mass determines how much of that heat can be stored. Insulation keeps the heat inside the space so that the energy stored by the mass is not lost to the outdoors. If the surface of equatorial-facing glazing is too small, then there will not be enough solar radiation penetrating into the space to heat it, and if there is too much glazing, there will be more losses than gains because of night losses. If there is not enough thermal mass, the space will have a large daily temperature swing, and it will be too hot during the day and too cold at night. If there is too much mass, some of it will be unused, but it will not affect the performance of the system, even though it could increase the load of a mechanical heating system.

There are some rules of thumb, but the best method to determine the required amount of glazing and thermal mass is to use energy modeling tools. The following two ratios of thermal mass to glazing are very rough rules of thumb for direct gain systems. Assuming the building has enough thermal storage mass in cold climates with average winter temperatures between −5°C and 0°C, there should be 0.2 to 0.45 m^2 of equatorial-facing glass for each square meter of interior floor area. In moderate climates with average winter temperatures between 5°C and 10°C, there should be 0.10 to 0.25 m^2 of equatorial-facing glass for each square meter of interior floor area. If night insulation is combined with glazing, these numbers can be higher.

As much thermal mass as possible should be placed in direct contact with the solar radiation inside the space. A larger surface area of the storage medium to glazing area will provide better heating, with a higher minimum air temperature and smaller temperature swing. For a 1:5 ratio of storage to glazing area, the fluctuation is 22°C, for 1:3 it is 14°C, and for a 1:9 it is 7°C (Balcomb 1992). For thermal mass exposed only to air and not to direct solar radiation, about four times as much thermal mass is required than if it was in direct contact. Furthermore, if the thermal mass is in direct sunlight, the temperature swing of the room air will be about half of the swing of the storage. However, if it is not in direct contact with solar radiation, the temperature swing of the air inside the space will be about twice that of the storage, so four times more. It is also important to remember that masonry surfaces are less effective on a daily basis beyond a depth of 10 mm, as explained in Chapter 7. This means that it is usually better to have the same amount of thermal mass distributed and exposed over a wider surface to capture more solar radiation than concentrated in a smaller area with more thickness.

Storage walls should not be set back more than 1.5 times the height of the collecting surface because if they are farther back than this distance they will probably not receive direct solar radiation. This means that an interior thermal storage wall should not be farther than 4.5 m away from a 3 m tall solar-collecting glazing wall.

10.4.2 Indirect Gain Systems

In an indirect gain system, the thermal storage materials are placed between the interior habitable space and the sun. These systems integrate collection, storage, and distribution functions within some part of the building envelope that encloses the living spaces. There is no direct heating from the sun to the space; the heating is provided by the element that has thermal mass to absorb the incident solar radiation that strikes it and then transfers it to the living space by conduction. Depending on the thickness of the material, this process can begin almost instantaneously or take many hours. This thermal mass is usually dark colored and has a glazed surface in the exterior face to create a small greenhouse effect reducing heat losses to the outdoors.

An indirect gain system uses between 30% and 45% of the solar energy that strikes the glass adjoining the thermal mass. The most common indirect gain systems are Trombe walls, mass walls, water walls, and roof ponds.

A Trombe wall has a glazed surface toward the exterior of the thermal mass separated by between 10 and 15 cm or more for maintenance. Solar radiation passes through this glazed surface to the

mass wall, hits it, and is absorbed by it, causing the surface of the masonry to warm up. The glazed surface on the exterior keeps the long wave radiation from being lost to the outside (Figure 10.7). This heat is transferred to the inner surface of the wall by conduction, from where it radiates and is convected to the interior space. The time lag and dampening of the wall depend on the type and thickness of material; a rough guide is about 45 minutes per inch of material. Trombe walls also have vents located toward the top and the bottom that allow for the distribution of the collected air (which can reach 60°C) by natural convection and thus can provide immediate heating inside the space. These vents can be closed at night to prevent reverse circulation (Figure 10.8). Typically, the openings should be between 1% and 3% of the wall area, and the distance between the bottom and top vent should be at least 1.8 m.

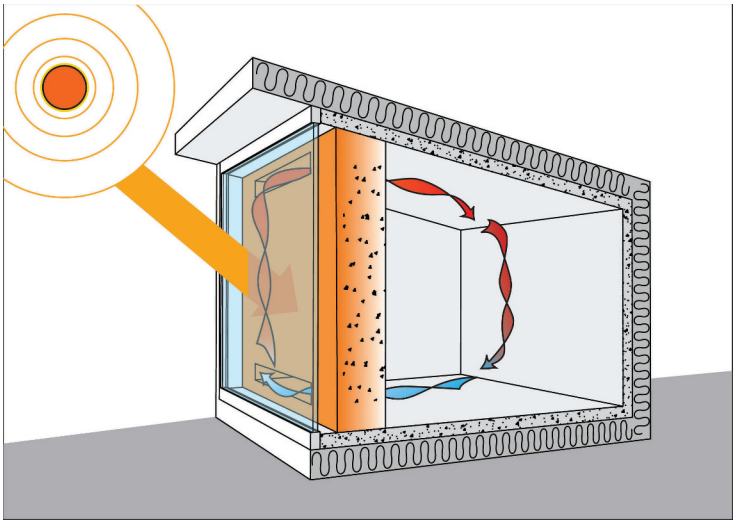

FIGURE 10.7 Trombe wall during the day.

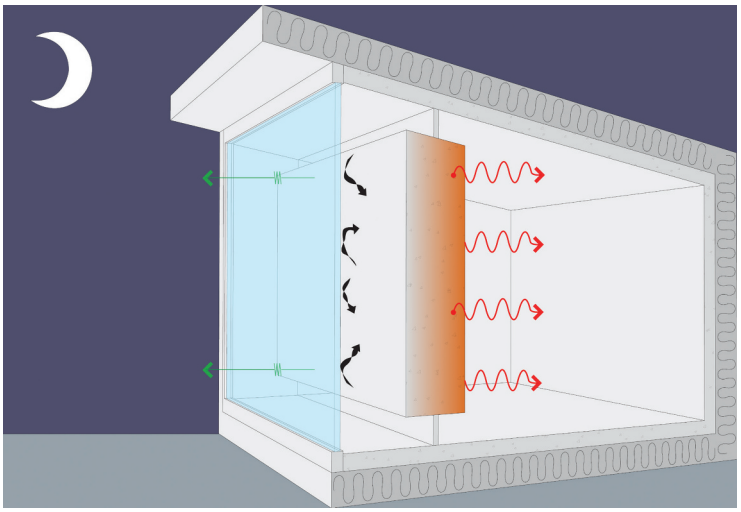

FIGURE 10.8 Trombe wall during the night.

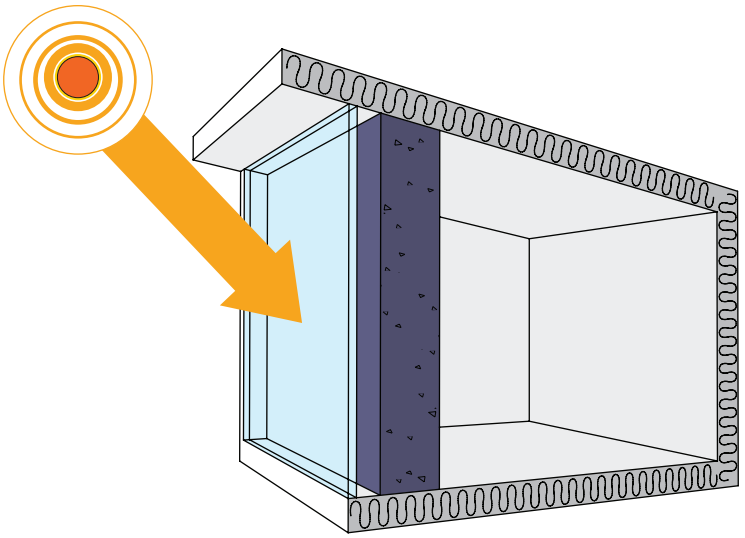

FIGURE 10.9 Mass wall early morning.

In a mass wall system, the thermal storage mass for the building is also a south-facing wall of masonry or concrete construction with the external surface glazed to reduce heat losses to the outside. The difference between a mass and a Trombe wall is that the Trombe wall has vents at the top and bottom to allow the air to circulate through the interior space, and the mass wall transmits the heat only by conduction to the interior surface and then radiation to the space. A cool mass wall is heated by the solar radiation during the morning (Figure 10.9), begins to heat up and transmit heat to the interior of the building during the day (Figure 10.10), and continues transmitting the heat collected from the solar radiation to the interior during the night (Figure 10.11) until heat inside the wall is depleted.

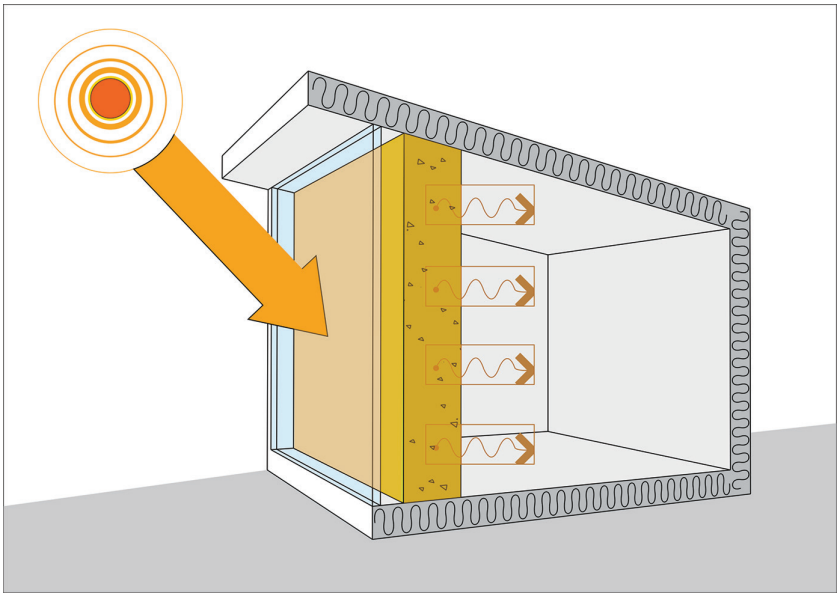

FIGURE 10.10 Mass wall midday.

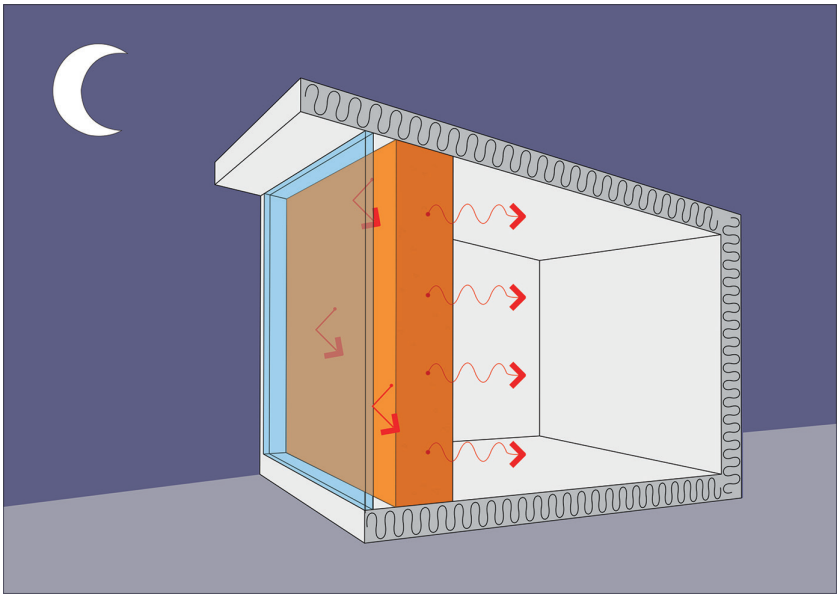

FIGURE 10.11 Mass wall night.

As with direct gain systems, it is difficult to give sizing rules of thumb because of the number of variables involved. However, several concepts are important to consider in the design of mass and Trombe walls: (1) Mass and Trombe walls should be between 15 and 30 cm thick for optimum performance. With even thicker walls (around 60 cm), thermal fluctuations inside the space are almost eliminated. (2) Different thicknesses also provide different time delays between the hot sunny exterior and the interior of the wall. Table 10.1 shows the temperature swing inside the space, and the time delay between the irradiation in a double-glazed concrete wall on a sunny day and the occurrence of the peak temperature inside the space that it encloses. (3) In the Trombe wall, the space can be heated by direct gain through the wall and convective loops through the vents during the day, and then through the thermal storage wall during the night. In mass walls with no vents there are no convective loops.

Mass and Trombe walls have several advantages. Glare, privacy, and ultraviolet degradation of fabrics are not a problem. Also, temperature swings in the living space are lower than with direct gain systems. And the time delay between absorption of the solar energy and delivery to the living space can be useful to better integrate to occupancy patterns and the outdoor requirements. There

TABLE 10.1

Thermal Lag and Indoor Temperature Swing in a Concrete Mass Wall with Exterior Double Glazing on a Sunny Day

Wall Thickness cm (in.)	Indoor Temperature Swing °C (°F)	Time of Peak Temperature Interior of the Space
20 cm (8 in.)	15°C (27°F)	6 p.m.
9.5 cm (12 in.)	7.2°C (13°F)	8 p.m.
40.5 cm (16 in.)	3.6°C (6.5°F)	10:30 p.m.
51 cm (20 in.)	1.7°C (3°F)	1:30 a.m.
61 cm (24 in.)	0.7°C (1.3°F)	4:30 a.m.

Source: Anderson, B. *Passive Solar Design Handbook*, Volume 1, U.S. Department of Energy, 1981.

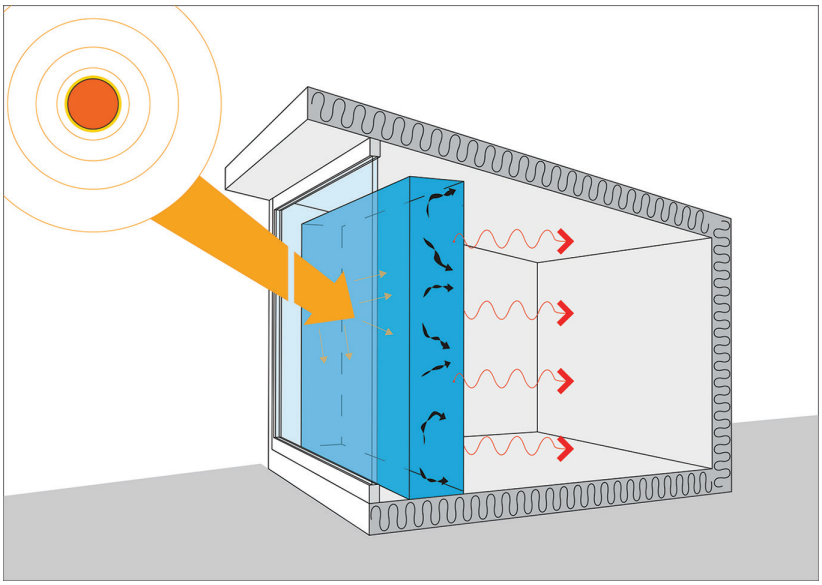

FIGURE 10.12 Water wall daytime.

are several disadvantages, though. The external surface of the mass wall is relatively hot and connected to the external climate, leading to considerable heat losses. In addition, two south walls are required—one glazed and one mass wall. Also, discomfort can be caused at either end of the heating season by overheated air or by radiation from the inside surface on warm evenings. These can be controlled by venting. There is no view or daylighting with mass or Trombe walls, and the glazed wall must have access for cleaning. Also, water can condense on the glass, reducing its performance. In northern latitudes in the winter, the mass can be a heating burden on very cold or cloudy days.

A water wall is another type of indirect gain system. It is very similar to the mass and Trombe wall systems except that water replaces the solid wall. Water works better as thermal mass because water has a greater heat capacity per unit volume than brick or concrete and because the convection currents within the water cause it to act like an almost isothermal heat storage system. Furthermore, because water is a fluid, it can be moved from one location to another, transferring this heat. During the daytime, the water wall absorbs and almost immediately transmits energy to the interior (Figure 10.12), and then during the night, the energy inside the wall continues to be transmitted to the interior of the space (Figure 10.13). A very rough rule of thumb for the design of water walls is to provide between 0.15 and 0.3 m^3 of water for each square meter of solar window. This is assuming that the interior water walls are dark colored and the wall receives direct solar radiation between the hours of 9 a.m. and 3 p.m.

Water walls have several advantages. The heat storage is isothermal, creating a lower external surface temperature and generating a lower temperature difference between the indoor and the outdoor and losing less energy to the outside. Also, glare, privacy, and ultraviolet degradation of fabrics are not a problem. Increased heat storage capacity means that the temperature swings in the living space are lower than with direct gain systems. And thermal storage can continue to supply energy to the living space well into the evening. Their disadvantages are first that water is difficult to contain and humidity can be a problem. Also, two south walls, one glazed and one mass, are required. Some water walls are in opaque containers, so there is no view or daylight. In addition, energy is lost to the outside air from the warm wall, and insulation can be expensive and awkward. If insufficient energy is provided during the day, as in a cloudy cold day, then the water wall will not be able to provide heat during the night and will be a heating burden for the mechanical systems. Another limitation for water walls and all wall indirect systems is the depth of the space determined by the height-to-depth ratio, a depth of about 8 m with typical wall heights.

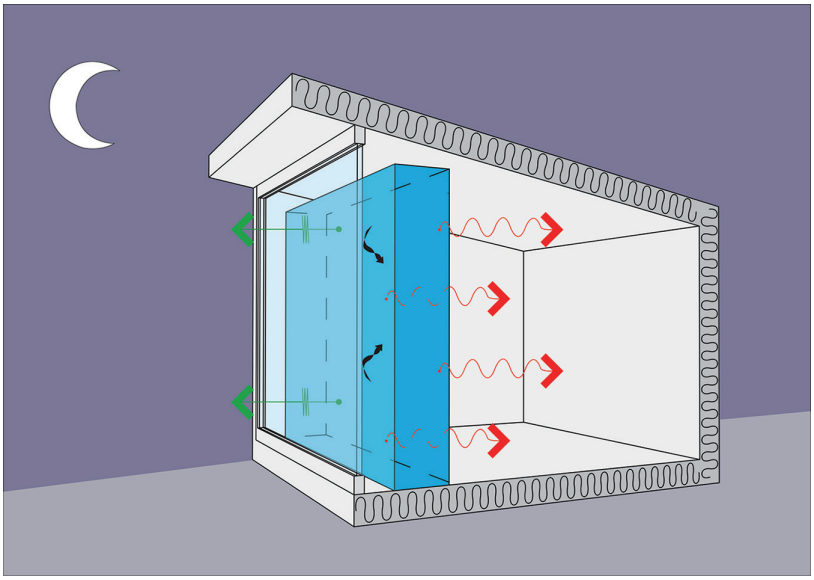

FIGURE 10.13 Water wall night.

A roof pond is an indirect gain heating system that can work as a radiant system, an evaporative cooling system, or both. A roof pond can be used for both heating and cooling. In a roof pond, thermal mass, generally in the form of enclosed waterbeds is placed horizontally, above an uninsulated ceiling of a building. In the winter, during the daytime, this mass is exposed to direct solar gain, heats up, and transmits this heat by conduction to the ceiling, below which will then transmit this heat by radiation and some convection to the space below (Figure 10.14). At night and when the sky is overcast, insulation covers the warmed water and reduces the heat loss to the exterior (Figure 10.15), so that the roof pond transfers the stored heat to the interior.

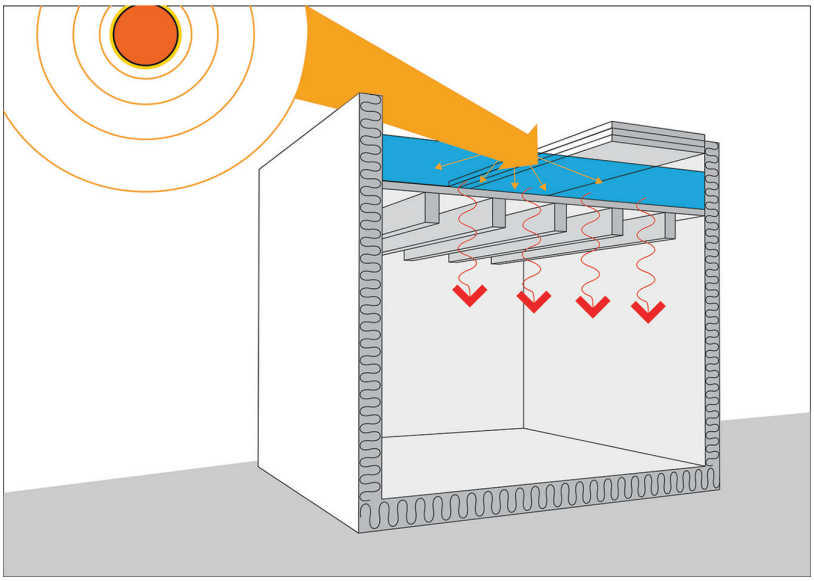

FIGURE 10.14 Roof pond during the winter day.

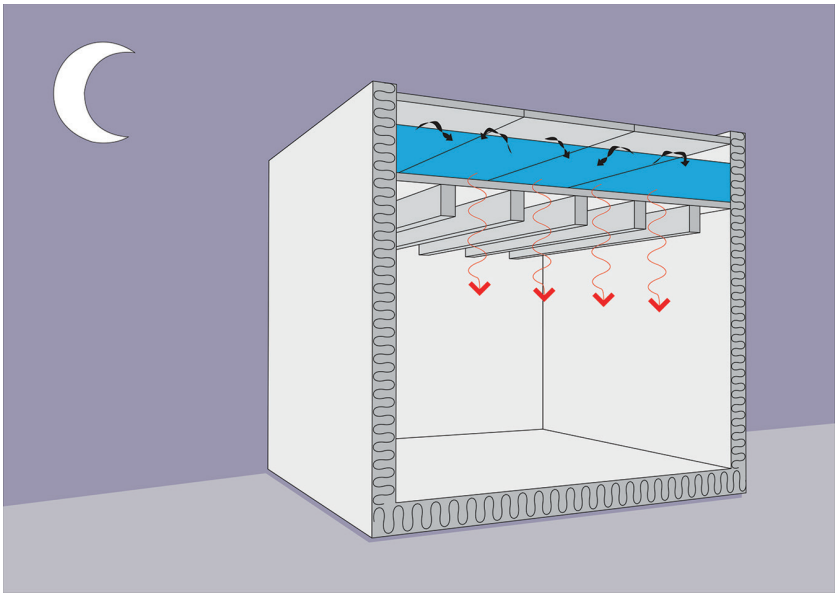

FIGURE 10.15 Roof pond during the winter night.

TABLE 10.2
Ratios of Roof Pond Collecting Surface per Unit of Floor Area (for Heating)

Average winter outdoor temperature (°C)	−10 to −4	−4 to 2	2 to 8
Double-glazed ponds with night insulation	Not feasible	0.85–1.0	0.60–0.90
Single-glazed ponds with night insulation and reflector	Not feasible	Not feasible	0.33–0.60
Double-glazed pond with night insulation	feasible	0.5–1.0	0.25–0.45
South-sloping collector cover with night insulation	0.60–1	0.40–0.60	0.20–0.40

Table 10.2 gives the ratios of roof pond collecting surface for each square unit of floor area in the interior space. Of course this will vary depending on location, exposure, and local conditions. The lower ratio given in Table 10.2 should be adequate at lower latitudes, while the higher ratio should be used at higher latitudes with colder climates. For latitudes higher than 36°, roof ponds require greater exposure to solar gains as well as additional requirements to reduce heat losses. Roof ponds can also be tilted toward the equator in higher latitudes to maximize winter heating.

An isolated gain system has its components separate from the main living area of the building that is heated. This ability to isolate the system from the primary building areas is what differentiates this system from other systems. There are two main types of isolated gain systems: sunrooms and convective loops through an air collector to a storage system in the house. An isolated gain system will use 15%–30% of the sunlight striking the glazing to heat the adjoining living areas. Solar energy is also retained in the sunroom itself.

Sunrooms consist of an attached sunspace with a glazed enclosure built on the equatorial-facing facade of the building. Depending on the climate and how the sunspace is used, there may be a heat storage wall separating the sunspace from the building or an additional storage system that stabilizes the temperature. Vents and shading can also help to control overheating.

During the daytime, the sunspace is heated by solar radiation. Some of this heat is conducted through a thermal storage wall separating the interior of the house with the sunspace, but is

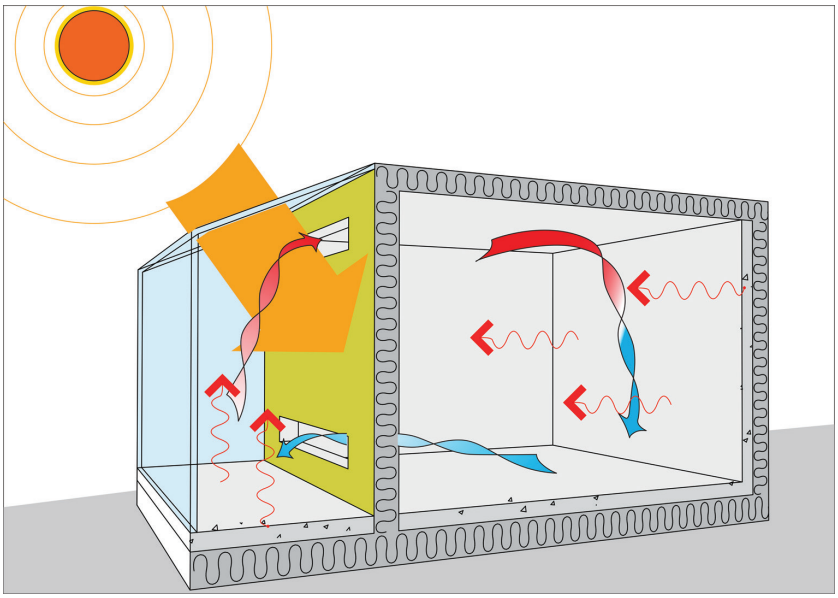

FIGURE 10.16 Isolated gain system day.

transferred mostly by convection with small fans to the interior space of the building. The sunspace works as a heat collector and a solarium for people and plants (Figure 10.16). During the night, the convection flows are blocked by closing the dampers in the vents, reducing heat transfer between the sunspace and the interior spaces (Figure 10.17). Generally, in cold climates, a sunspace design will use between 0.65 and 1.5 m^2 of a south-facing double-glazed collecting surface for each square meter of floor area in the adjacent living space. In more moderate climates, this number can be reduced to between 0.3 and 0.9 m^2 per square meter of floor area. The main difficulty with attached

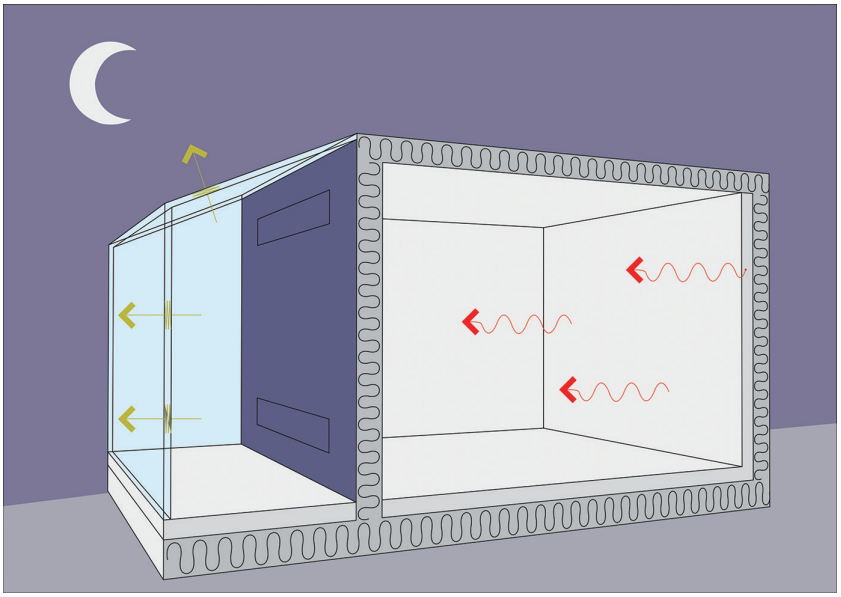

FIGURE 10.17 Isolated gain system night.

sunspaces is that they gain and lose heat rapidly, overheating during the day because they must be warmed up substantially to provide heat to the adjacent space, and then they overcool rapidly at night because they quickly lose heat through the glazing. This makes it difficult to use these spaces for a significant amount of time during the day or night.

10.5 EFFECTS OF DESIGN STRATEGIES ON EMISSIONS

Many different types of design strategies can affect emissions in different ways. For example, installing overhangs, adding insulation to the walls, using better windows, or implementing passive solar strategies will reduce emissions from building energy; living close to work or working at home will reduce emissions from transportation; and recycling will reduce emissions from waste decomposition and fabrication of materials. Some energy-related strategies have been compared to illustrate their effect on a building's greenhouse gas (GHG) emissions. The effect of these design strategies on emissions is studied in four climates. The strategies are (1) the insulation level of the wall, (2) the characteristics of the windows, (3) the efficiency of the air-conditioning, and (4) heating systems; the climates are hot and dry, hot and humid, cold, and temperate. The same single-family house with the same building emissions data was studied in each of the four climates with three levels of performance (Tables 10.3 through 10.5). The lowest level of performance is a building with

TABLE 10.3
Envelope Characteristics

Envelope Components (W/m² K)	Wall	Roof	Floor
Low insulation	1.46	1.53	0.53
Medium insulation as defined by the California Title 24 Energy Code	0.27	0.15	0.29
Super-insulated Passive house Standard	0.15	0.13	0.15

TABLE 10.4
Window Characteristics

	SHGC	Transmissivity	U (W/m² K)
Single-glazed	0.75	0.77	7.2
Double-glazed	0.55	0.55	3.12
Triple-glazed	0.5	0.51	0.79

TABLE 10.5
Mechanical Systems

	Annual Fuel Utilization Furnace (AFUE)	Air Conditioning (SEER)
Low-efficiency	72	8.9
Medium-efficiency	78	13
High-efficiency	97	18

envelope conditions that would not pass code in many countries, but that are still allowed in many countries in the world without energy codes. The effect of implementing two passive design strategies (direct gain in the cold climate and night ventilation in the hot and dry) is also calculated. The tightness of the envelope is constant at a maximum of one air change per hour, which is not difficult to achieve. This value was not modified so as to not introduce another variable in the design; even though the more insulated buildings built with structural insulated panels (SIPs) would probably be much tighter, improving its performance.

GHG emissions from heating (Table 10.6) clearly demonstrate the effect of a better envelope on performance. In the cold climate, the house with the low-performance furnace (72% annual fuel utilization efficiency [AFUE]), poor insulation, and single-glazed windows has emissions of 13,466 kg CO_2e. When the furnace is updated to 97% AFUE and the house is super-insulated, the emissions are reduced to 1,091 kg CO_2e, which is only 10.1% of the previous amount. If the windows are relocated to the south side and reduced on the east, west, and north sides; if an overhang is added on the south side; and if the floors are changed to concrete slabs, the emissions are further reduced to only 291 kg CO_2e (Figure 10.18), which is only 2.2% of the initial emissions in the low-performance house. Implementing passive strategies improves performance at all levels. Adding these three additional "passive solar" changes (windows to the south, overhangs, and concrete slabs) reduces the emissions by about 9% in the low-quality envelope, 37% in the code-quality envelope, and 73% in the high-quality envelope.

Emissions from cooling are also affected by the quality of the envelope and the efficiency of the heating, ventilating and air conditioning (HVAC) system. In the hot and dry climate, the emissions with the low-performance air-conditioning system (10.9 SEER) in the poorly insulated house with single-glazed windows are 9,523 kg CO_2e. When the air conditioning is updated to 18 SEER and the house is super-insulated (see Table 10.5), the emissions are reduced to 1,994 kg CO_2e, which is only 20.9% of the previous amount (Table 10.7). If night ventilation was added to the best envelope with the highest-efficiency air-conditioning system, the emissions would be further reduced to 732 kg CO_2e, which is only 7.7% of the original value (Figure 10.19). Night ventilation, shading of the south windows, and thermal mass reduced emissions in all building qualities in the hot and dry climate. Emissions were reduced by about 26% in the poorly insulated building, 55% in the code building, and 63% in the super-insulated building.

TABLE 10.6
GHG Heating Emissions (kg CO_2e)

Heating Climate	Cold			Temperature			Hot and Dry			Hot and Humid		
Furnace Efficiency AFUE	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High
No insulation and single-glazed	13466	12429	9991	2596	2395	1928	1710	1575	1265	261	239	190
Code insulation and double-glazed	3817	3524	2829	407	369	299	358	331	266	38	33	27
Super-insulated and triple-glazed	1477	1363	1091	16	16	16	33	33	27	5	5	5

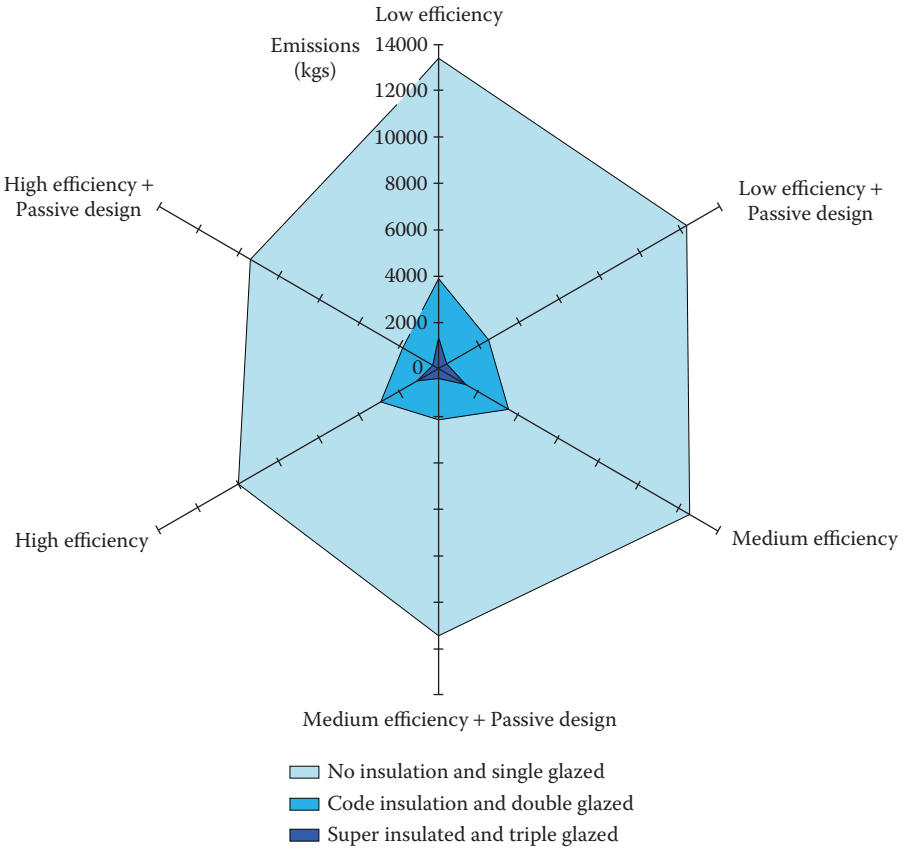

FIGURE 10.18 Emissions in cold climate with different strategies including passive strategies (direct solar gain).

TABLE 10.7
GHG Emissions from Cooling (kg CO_2e)

Climate	Cold			Temperature			Hot and Dry			Hot and Humid		
Cooling SEER	**Low**	**Medium**	**High**	**Low**	**Medium**	**High**	**Low**	**Medium**	**High**	**Low**	**Medium**	**High**
No insulation and single-glazed	1893	1296	936	1784	1221	882	9523	6519	4708	6597	4517	3262
Code insulation and double-glazed	1127	771	557	1238	848	612	5100	3491	2522	4994	2741	1980
Super-insulated and triple-glazed	1259	862	622	1605	1091	787	4032	2748	1994	757	757	757

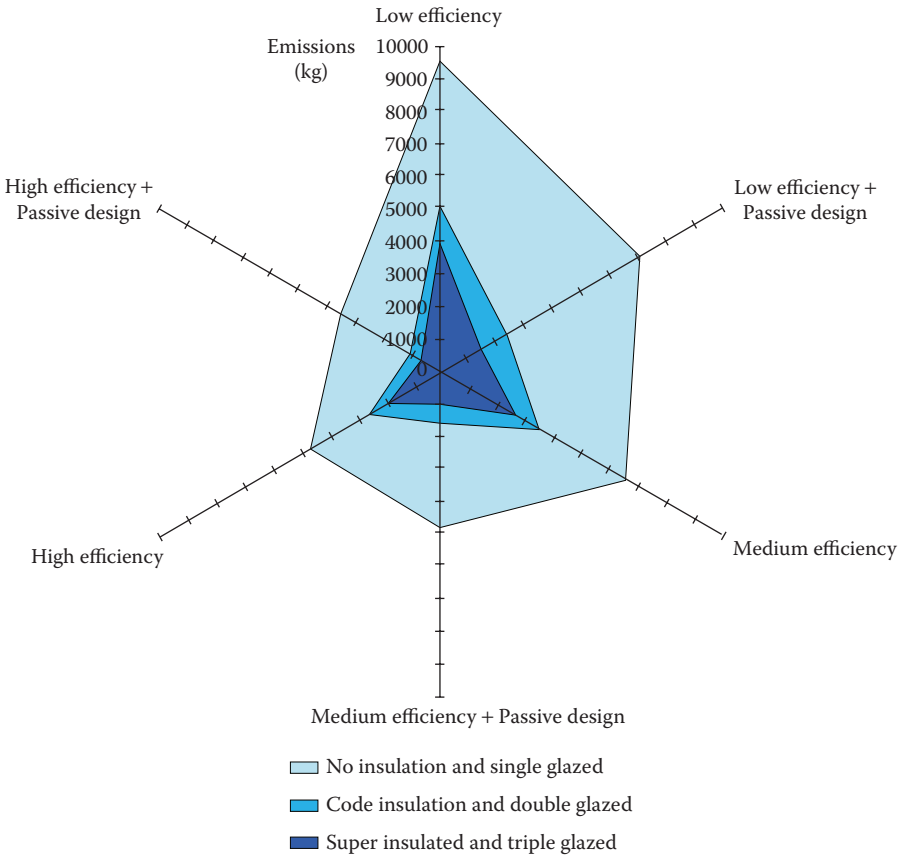

FIGURE 10.19 Emissions in hot and dry climates including passive strategies (night ventilation.)

Just applying these design strategies (better envelope, more efficient mechanical, and passive strategies) can reduce emissions from 13,466 kg CO_2e in the uninsulated building with bad windows and inefficient mechanical system to 291 kg CO_2e with the super-insulated building in the cold climate and from 9,523 to 732 kg CO_2e in the hot and dry climate, clearly demonstrating the power of energy-efficient and climate-responsive design.

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11 Building Simulations and the Design of Low Carbon Buildings

Carbon-neutral design focuses on buildings that reduce or eliminate carbon dioxide emissions throughout its life cycle. Low carbon buildings are, by their very nature, high-performing buildings. A high-performance building integrates and optimizes, on a life-cycle basis all major high-performance attributes, including energy conservation, environment, safety, security, durability, accessibility, cost–benefit, productivity, sustainability, functionality, and operational considerations (United States Energy Independence and Security Act of 2007). The goal of using simulations during the architectural design process is typically to achieve high-performing, low energy, carbon-neutral buildings that are also comfortable to its occupants. There is no clear threshold that indicates when a building becomes a high-performance building; however, it is clear that it must have a considerably better performance than similar buildings in the same location and climate. A method to evaluate based on emissions is to use Architecture 2030's challenge for buildings. If the building is designed better than the 2030 challenge [currently 70% less energy than a Commercial Buildings Energy Consumption Survey (CBECS) reference building], then the building is a high-performing building.

11.1 PERFORMANCE SIMULATION

Building energy performance simulation describes the process and tools that permit architects and engineers to analyze the effects of certain building properties, such as form, size, orientation, and mechanical systems on variables such as energy consumption and daylight.

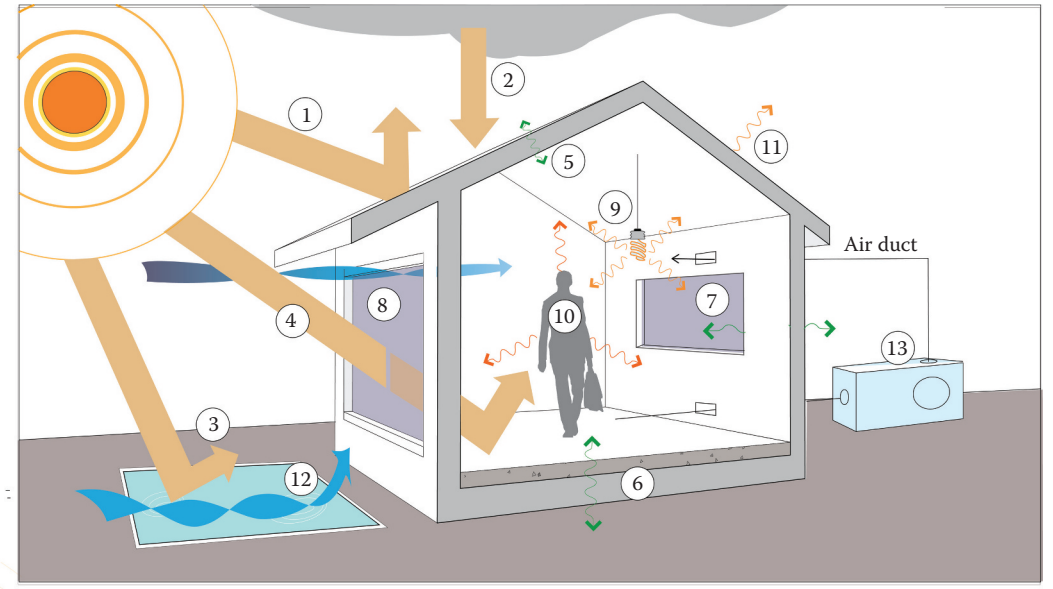
Spitler (2006) states that the simulation of building thermal performance using digital computers has been an active area of investigation since the 1960s. Much of the early work focused on energy analysis, which still continues to be an important area of work and research. However, over time, the simulation domain has grown to include more areas and there are now tools that can simulate many environmental factors such as the simulation of heat and moisture transfer in the building fabric, airflow through and outside the building, daylight, glare, and multiple systems such as photovoltaic or solar hot water. At the same time, faster and more powerful computers combined with easier to use graphical user interfaces have made these tools more powerful and available to more users.

Performance simulation has typically been seen as a very complicated and technical process that only an engineer is able to perform. However, even if some engineers have the technical knowledge to understand the thermal and luminous processes, they do not always have the necessary design skills to provide more than technical advice on very specific issues, usually in the form of technical reports, which do not always provide a significant contribution to broader or current design issues. Very simple design (VSD) tools, proposed by La Roche and Liggett (2001), and discussed in Chapter 2, should be easy to use so that more designers adopt them as part of their design process, improving the performance of more buildings. Ideally all tools should be both easy to use and powerful. There is value in all modeling tools, but high cost and difficulty to use reduce the value of the tool which can then only be used in the design of a few exemplary buildings. It is important to have access to simulation tools, with clear graphical user interfaces and sufficient precision so that they can be used in the conceptual design phase.

Heating, ventilation and air conditioning (HVAC) and lighting systems in buildings are designed to provide thermal and visual comfort for the occupants, but in doing so are also the major consumers of energy within the building sector. Space heating and cooling, water heating, and lighting can account for 70% of a building's site energy. The goal of energy conservation measures (ECM) is to reduce energy consumption, operating costs, and greenhouse gas (GHG) emissions from buildings, without reducing comfort levels; in fact they can also improve comfort. Performance simulations allow to quickly compare options and test the effect of mechanical and architectural strategies on daylighting, energy consumption, and thermal comfort, permitting architects to compare the effects of different design moves.

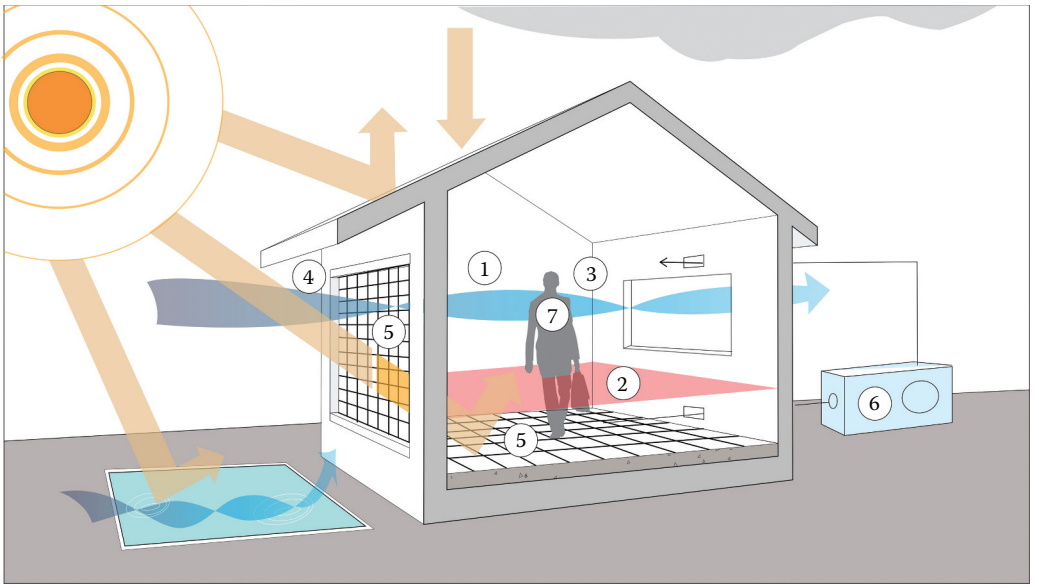
In order to maintain temperatures in the thermal comfort zone, a certain amount of energy needs to be added to or removed from the building. Energy must be added when the indoor temperature is below the comfort zone (heating load) and must be removed when it is above the comfort zone (cooling load) (see Chapter 8 for a more detailed description of these processes). For two given buildings (identical), one located in a warm climate will have a larger cooling load, while another located in a cold climate will have a larger heating load. The amount of energy is a function of the outdoor climate, building envelope properties, and indoor conditions of occupancy, such as the schedule and plug loads. This energy constitutes a load on the HVAC system (for heat and moisture) installed to condition the building space and thus, a building space load (BSL) (Harishn and Kumar, 2016). Simulation programs must be able to estimate the factors that affect thermal comfort and energy consumption, and to do this they accept different types of inputs depending on the simulation required. These inputs include building geometry, system properties, and operation schedules.

Most building simulation programs analyze energy flows in the building. Figure 11.1 shows the environmental, envelope, and internal factors that affect thermal comfort and heating and cooling



1 Beam (direct) solar radiation
2 Diffuse solar radiation
3 Ground reflected solar radiation
4 Window solar radiation
5 Envelope heat conduction
6 Ground heat conduction
7 Window heat conduction
8 Infiltration heat transfer
9 Electric lights and appliances
10 Occupants heat contribution
11 Sky long wave radiation
12 Evaporative cooling
13 Mechanical heating and cooling

FIGURE 11.1 Thermal exchange between a building with a HVAC and the outdoor environment.



1 Computer fluid dynamics
2 Illuminance
3 Luminance
4 Shade design
5 Solar irradiation
6 Energy
7 Thermal comfort

FIGURE 11.2 Examples of building simulations.

loads in a building with a mechanical cooling and heating system. Passive heating and cooling strategies are important because they reduce the heating and cooling loads and GHG emissions (if the energy used by mechanical systems to offset the loads is nonrenewable). In temperate climates, buildings can be designed so that mechanical heating and cooling loads can be greatly reduced.

Simulation modeling enables designers to make appropriate decisions on skin configuration, shading devices, glass choices, conditioning approaches, equipment selection, or occupant comfort, performance, cost, and schedule. Figure 11.2 shows typical simulations that can be performed to understand the effects of these variables on thermal comfort and energy consumption.

The building simulation discipline is evolving and maturing and improvements are continually being made to add more robustness and fidelity (Hensen and Lamberts, 2011). The development, evaluation, use in practice and standardization of the programs are of growing importance. Furthermore all building simulation experts acknowledge that implementation in the early design phases is more cost-effective than in later phases and much more effective than to implement a corrective measure in a building that was not appropriately designed. Nevertheless building simulation is not yet standard practice in projects, and when implemented it is mostly at a later phase because it is required by code or a green building rating system or not at all.

Robinson (2008, cited in Hensen and Lamberts, 2011) states that all simulation models are simplifications of reality … the overarching requirement is to avoid the development of a model that is more complex than necessary. In general, the goal should be to keep the model as simple as possible to meet the objectives of the simulation study (Robinson, 2008, cited in Hensen and Lamberts, 2011). It is still very difficult to use simulation programs directly inside computer-aided design (CAD) program and most digital models that are used with energy simulation programs have more information than is required and must be simplified.

11.2 TYPES OF BUILDING PERFORMANCE SIMULATION

According to the AIA Architect's guide to Integrating Energy Modeling in the Design Process (2012), there are four common types of energy/performance modeling: design performance modeling (DPM), building energy modeling (BEM), building operations modeling (BOM), and project resource modeling (PRM).

DPM informs design decisions by predicting a building's performance with respect to energy efficiency, daylight penetration, glare control, thermal comfort, natural ventilation, and similar factors. It is typically done during the early stages of design, before engineering systems are incorporated.

BEM predicts a building's anticipated energy use and corresponding energy savings, as compared to a standard baseline. In doing so, it demonstrates project compliance with local, regional or national energy codes. BEM predicts energy performance based on typical meteorological year (TMY) data, as well as assumptions about building operation and maintenance.

BOM introduces actual utility bills, use patterns, hours of operation, functioning of systems, and real weather conditions for a completed building into a model structured similarly to the Building Energy Model.

PRM is the most extensive and broad of the four most common forms of modeling. It assesses multiple resource issues that affect and are affected by the development of a project, including energy, water, material selection, and solid waste. It may also include transportation, primary growth issues, manufacturing, social and agricultural elements, embodied energy, carbon emissions, health, and other factors.

11.3 PERFORMANCE SIMULATIONS IN THE DESIGN PROCESS

To improve building performance and reduce carbon emissions, both digital and analogue tools should be integrated in the design process. Different types of simulation tools are implemented to solve problems at multiple scales during the design process. Some tools are better for quick initial studies, while other tools provide more precision but require more information and time to collect and then process the information. This section does not explain all possible forms of building simulations; in fact it only shows three types. However, these can help the readers to understand and then create their own personal workflows using different tools.

While the classification of the building simulations discussed in Section 11.2 refer to the objective of the simulation, Anderson (2014) also classifies building performance simulation in three types based on the number of variables that are considered: single aspect analysis, shoebox analysis, and while building energy simulation.

Single aspect analysis evaluates a design to determine the effects of a single factor. Common examples are solar irradiation, illuminance, and luminance and since this analysis just focuses on one variable it is relatively quick and accurate. Even though this analysis is of only one variable there are already many possible ways to analyze one variable. It is important to focus on a key aspect that can provide meaningful results. Outputs from a single aspect analysis can be used as inputs in whole building energy simulation (WBES).

The design of the façade in a medical office building in southern California is described as an example of single aspect analysis. The project had been already designed to conceptual level by another firm with a very simple façade using a tilt up construction system which also provided limitations in the horizontal dimensions of the window. When CallisonRTKL's design team took the project, they decided with the performance-driven design (PDD) team to improve the occupant experience in the west-facing waiting area, providing more and better daylight with less glare. Figure 11.3 shows the project as it was originally designed. All windows in all orientations

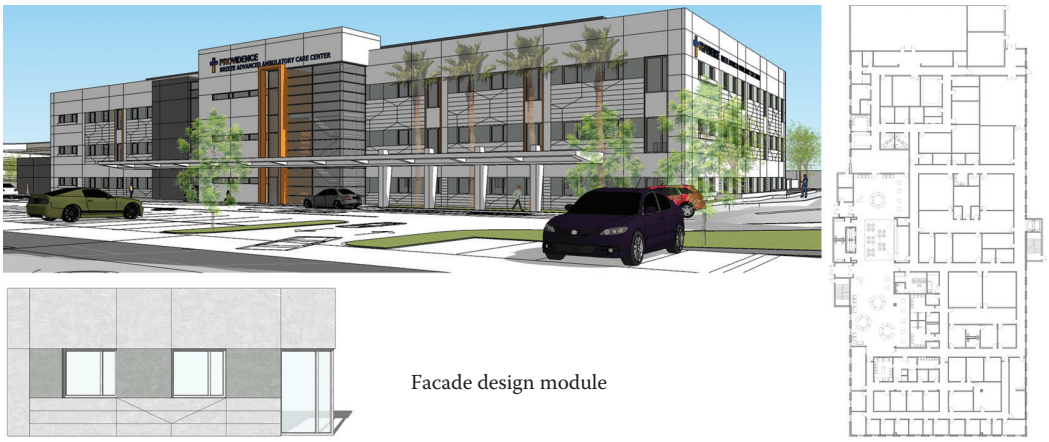


FIGURE 11.3 Original design for medical office building facade. (Courtesy of CallisonRTKL.)

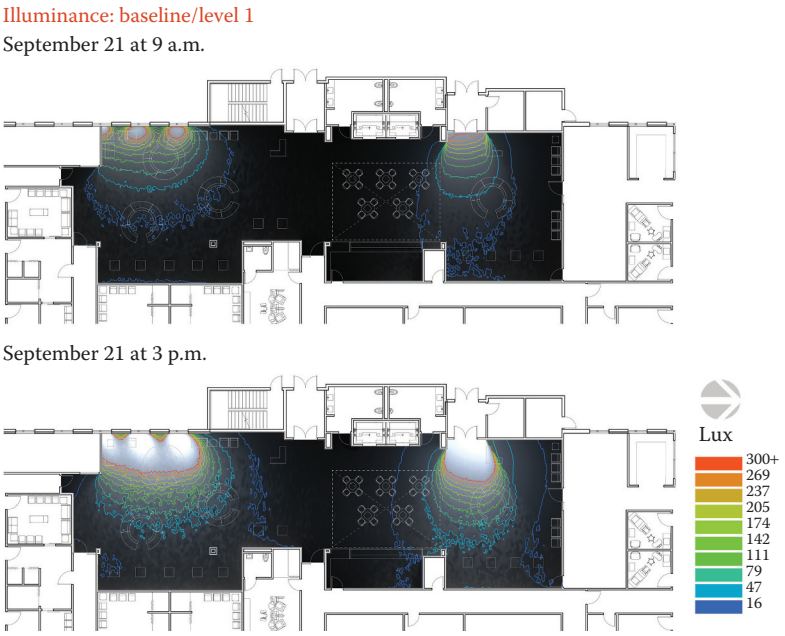


FIGURE 11.4 Daylight in Level 1 of original design for medical office building facade. (Courtesy of CallisonRTKL.)

are the same. Figure 11.4 shows daylight levels calculated with IESve and Radiance at 9 a.m. and 3 p.m. on September 21. Even with this relatively low value, daylight does not penetrate very deeply into the space, especially in the morning when the sun is at the other side of the façade. In the afternoon, it is very bright close to the window with little daylight penetration. Several window options were studied to improve this, including a floor to ceiling version. Figures 11.5 and 11.6 show a proposal with a slightly larger window and a light shelf. Even though light shelves are usually proposed in equatorial facing elevations with abundant direct light it provided a reasonable

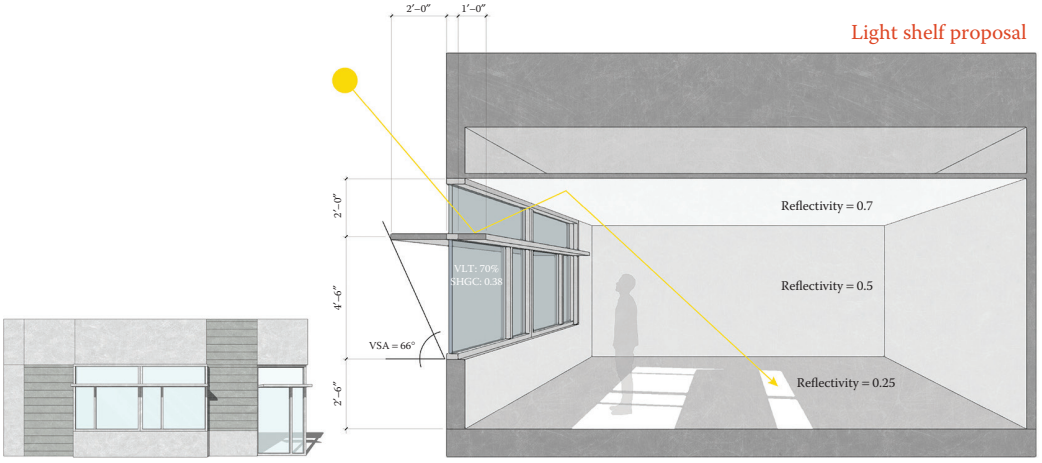


FIGURE 11.5 Section through light shelf proposal. (Courtesy of CallisonRTKL.)

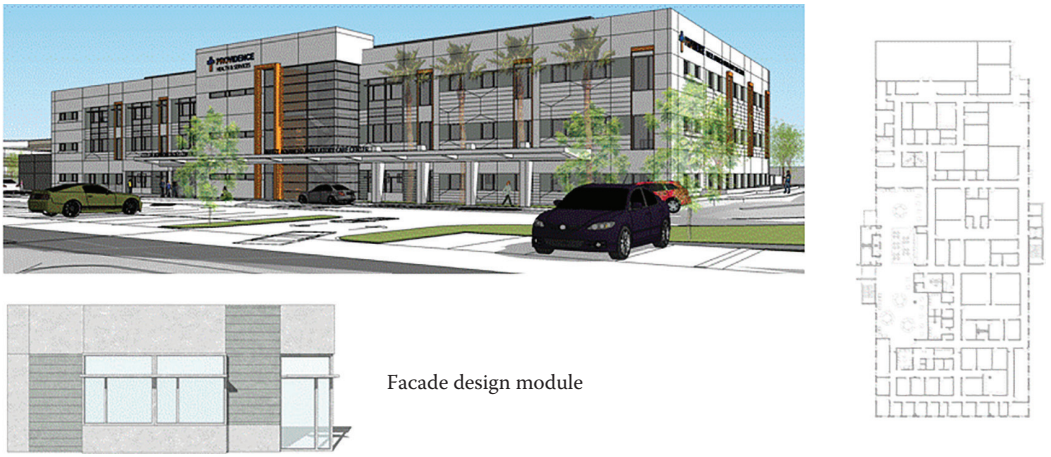


FIGURE 11.6 Façade of light shelf proposal with glass enclosed staircase. (Courtesy of CallisonRTKL.)

option in this west-facing façade. Figure 11.7 shows an option, which includes fire rated glass in the stairs, and increases daylight to the interior while reducing glare close to the window. Figure 11.8 shows another option with the same window design but with a different layout for the stairs that does not include the glass. The client selected the option in Figure 11.7 with the glass enclosed stairs. Glare was also studied using IESve and Radiance. In all options, due to the west-facing orientation, there will still be glare during the late afternoon, and some operable indoor shading will be needed during critical hours.

Spatial daylight autonomy (sDA) would have provided a better description of daylight levels during the whole year; however, a two point in time analysis was preferred. Morning and afternoon conditions were studied symmetrically around solar noon, with different solar positions, one with the sun in the back and one in the front. It is clear that even in a single aspect analysis there can be multiple analysis options with different tools that can be performed to obtain meaningful results. Each of them has advantages and limitations and the strategy should be selected to generate the most precise results with the least amount of time invested. Additional options include an hourly simulation from 8 a.m. to 6 p.m., more simulations later in the afternoon at critical hours, an sDA, or combination of all of these. The main goals are typically to determine the highest performing option and the values that predict future conditions.

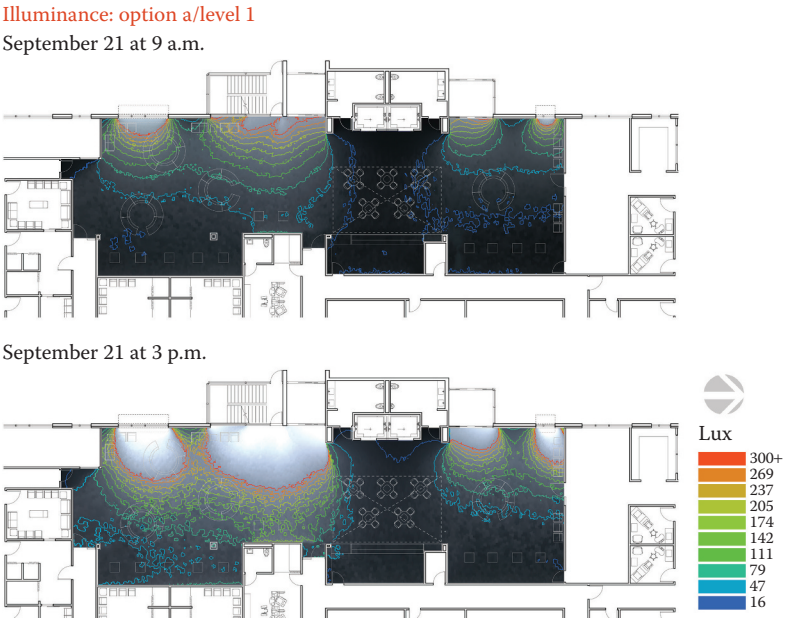


FIGURE 11.7 Daylight levels with light shelf proposal and glass enclosed staircase. (Courtesy of CallisonRTKL.)

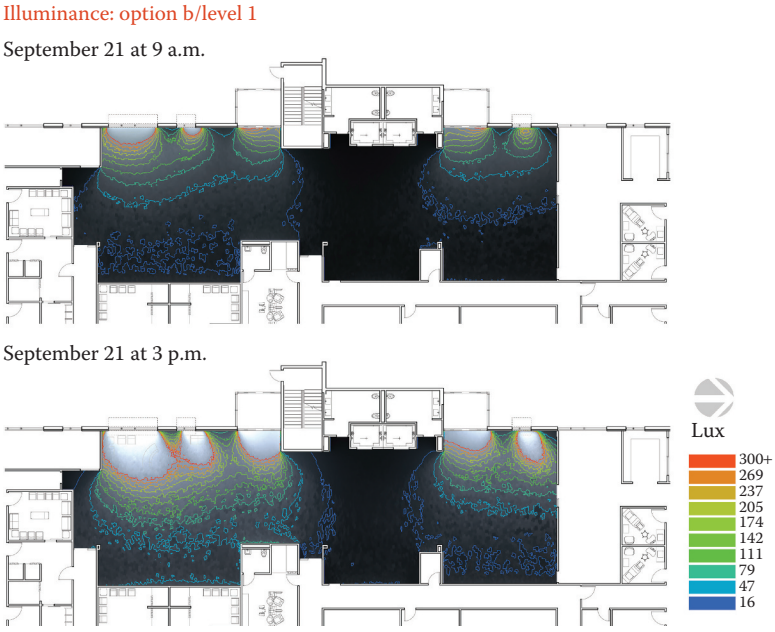


FIGURE 11.8 Daylight levels with light shelf proposal and rotated staircase. (Courtesy of CallisonRTKL.)

WBES considers most energy-related aspects of an entire building. It is much more complex and takes considerably more time than a single aspect analysis and provides a detailed account of a building's energy use. WBES can provide early benefits; however, it is usually run toward the end as a compliance tool for energy codes or green building rating systems such as LEED.

Shoebox analysis considers many of the variables that are also considered in a WBES model, but typically use averaged data for the default settings, accounting for mechanical systems and

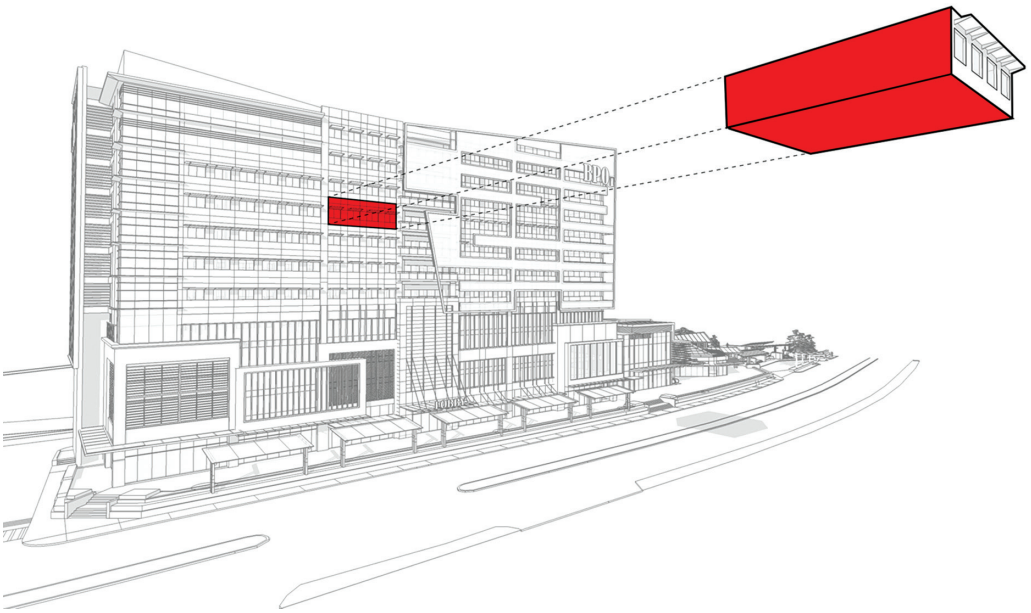


FIGURE 11.9 Shoebox energy modeling. (Courtesy of CallisonRTKL.)

adiabatic walls. This type of analysis allows the designer to focus on the design of an external facade through which most of the heat transfer will occur. Shoebox analysis is a very useful tool to compare façade options for spaces that are repeated multiple times in the same orientation, such as guestrooms in hotels, classrooms in schools, and patient rooms in hospitals. COMFEN from Lawrence Berkeley National Laboratory is an example of a shoebox modeling program (Figure 11.9).

11.4 EMPHASIZING "DESIGN" IN THE DESIGN SIMULATION PROCESS

It is necessary to move a step beyond performance simulation as a purely evaluative process to one that is more active in the generation of architectural design concepts, in which performance simulations are intimately connected with the design process during the evaluation and generation of ideas, responding to natural forces, design intent, and client expectation.

Reinforcing the potential for concept development in a team that has traditionally only been technically oriented has opened the door to a more intensive implementation of PDD strategies in more projects. In addition to comparing design options, it is also possible for the building simulation team to propose options and contribute in the generation of design ideas and concepts. This enhanced simulation process inspires/promotes innovation and creative architecture. This process can evolve using the most effective tools to solve the issues at hand.

The process starts with setting the goals and continues with the implementation of multiple strategies to improve building performance in different areas. The design process should be adapted to the unique circumstances of each project and support project teams and clients. Data and results must be transferable from one area to another using common metrics as much as possible. This process includes tools to improve building performance in specific areas (Figure 11.10). It differs from the diagram proposed in Chapter 2, in that this process includes time in the "x" axis and includes a more limited set of strategies, all of them in the building simulation field.

In Figure 11.10, the "x" axis indicates time and the vertical columns are the typical design phases: conceptual design, CnD, schematic design SD, design development DD, construction documents CD, construction administration CA, and operation and maintenance O&M. The horizontal

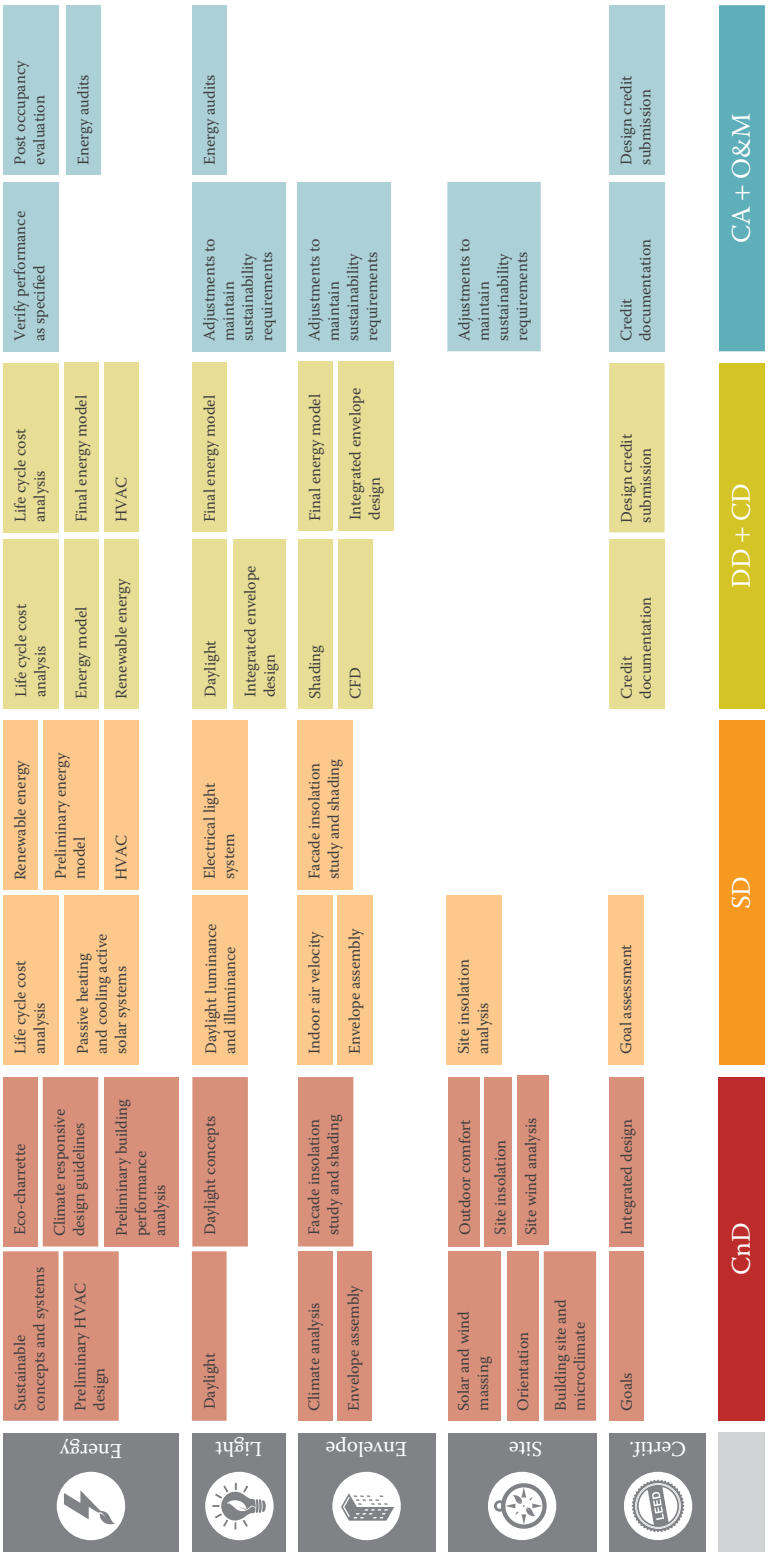


FIGURE 11.10 Performance simulation design process.

bands are some of the topics that designers must address during the design process: site, envelope, light, and energy. These categories do not encompass all performance categories and can be modified by project. Rectangles in the intersection of these two represent the strategies that can be implemented in each area. Each of these can include different digital and analogue tools and can be explained using detailed workflow diagrams that include tools and steps. These workflows are useful to understand the strategies and tools needed to accomplish goals. Ideally, these should be done in-house, working closely with designers or done by the designers. The diagram shows several processes that can be implemented to improve building performance and reduce carbon emissions using building simulations. The goal is not to include all possible simulations in one diagram, but is instead to describe a potential organization method and some strategies that can be implemented by architects, students, and energy modelers. These workflows are not prescriptive, every designer/modeler will probably have his/her own workflow; however, these can be used as a starting point to generate personalized workflows using different tools.

11.5 SIMULATION WORKFLOWS

This section includes an explanation, with examples, of three strategies from Figure 11.10, shade, daylight and outdoor comfort. In no means the description of these is meant to be exhaustive or prescriptive. Instead it provides a general idea on how some of these processes can be implemented to provide useful results.

11.5.1 Envelope and Shade

The building envelope regulates multiple types of interactions between the indoor and outdoor environments, regulating heat gains and losses, providing daylight, controlling glare, and providing views when needed. A study of the envelope usually begins with a solar analysis of the facades on different orientations, calculating solar gains during peak cooling and heating hours and for complete cooling or heating seasons. The effects on daylight (luminance and illuminance) and energy consumption are also calculated. This integrated analysis process can be used for whole facades or parts of them to determine the best shading option to control heat, daylight, glare, and views.

Figures 11.11 and 11.12 show a typical workflow for envelope analysis which can be used for the design of fixed shading devices using analogue and digital tools. Understanding the process and workflows is important to correctly design effective and creative shading devices. The process follows several steps: 1) climate analysis and calculation of overheated and under-heated periods; 2) solar analysis; 3) shade design; 4) performance evaluation; 5) redesign/adjustment.

1. *Climate Analysis*: Shade design usually begins with a climate analysis. The most important factors to analyse in climate are those that affect thermal comfort, energy consumption and GHG emissions in buildings. Typically temperature, direct and diffuse solar radiation, relative humidity and wind speed and direction are studied using a weather file. Temperature and solar radiation (direct and diffuse) are critical to accurately determine cooling and heating seasons, which are never symmetrical. These periods determine when solar radiation should be promoted or blocked. EPW weather files can be obtained for free from the department of energy at https://energyplus.net/weather. For climate analysis there are several free and easy to use tools. Climate Consultant available from the University of California Los Angeles, is a very easy to use well designed tool that also provides design advice based on the climate and links to the 2030 Palette with examples of strategies for buildings in different climates (http://2030palette.org/). A tool developed at MIT allows for visualization of epw files https://mdahlhausen.github.io/epwvis/ and Grasshopper with Ladybug are also relatively easy to use.

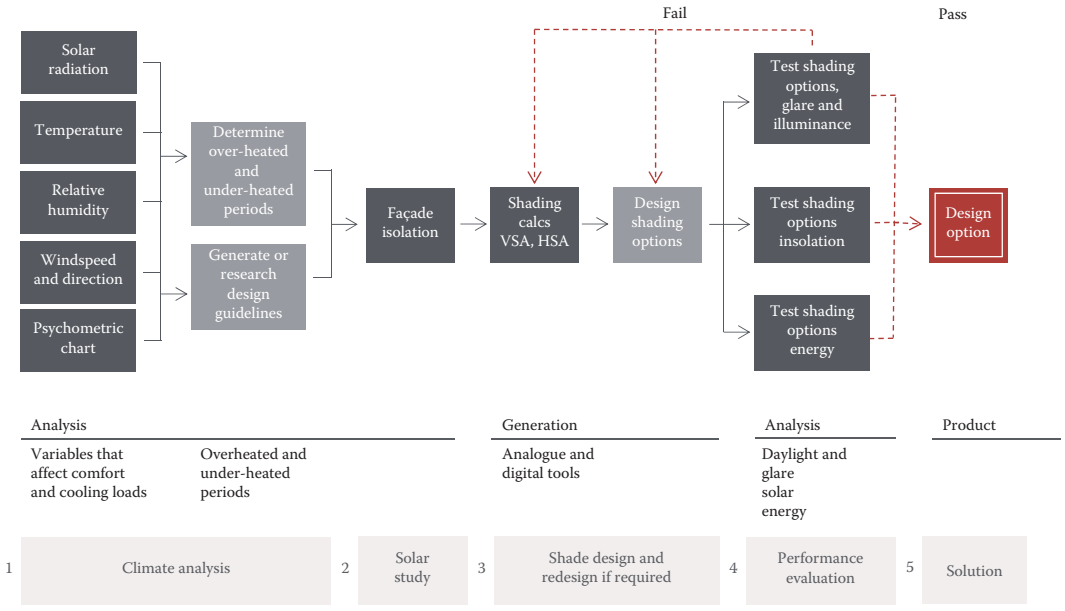


FIGURE 11.11 Envelope analysis workflow. (Courtesy of CallisonRTKL.)

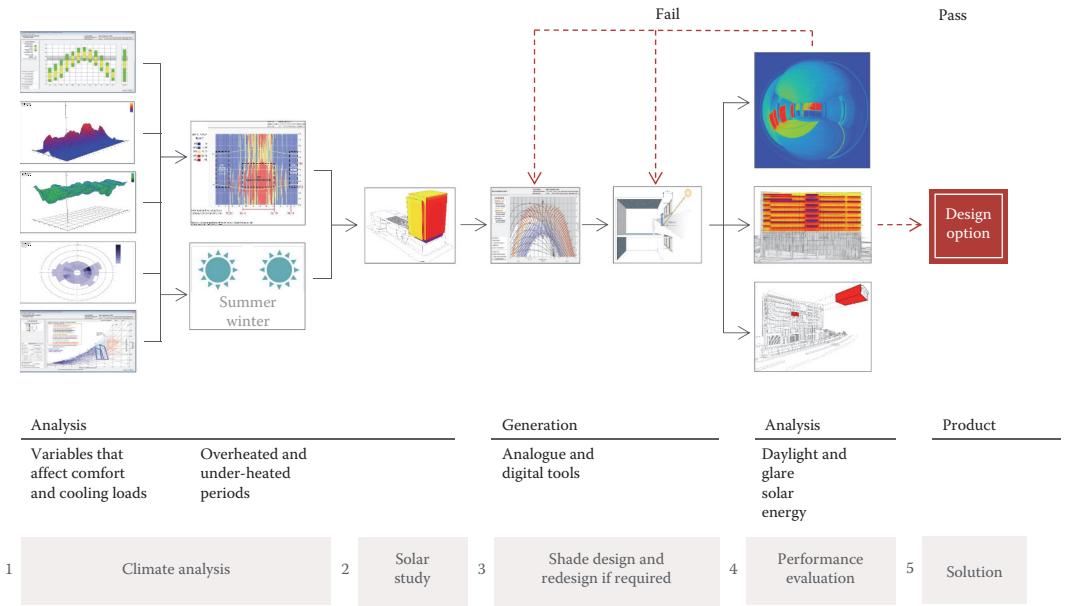


FIGURE 11.12 Envelope analysis workflow with icons. (Courtesy of CallisonRTKL.)

Climate data helps to determine overheated and under heated periods, which are used for summer and winter insolation analysis, self-shading studies, to determine critical facades, and to design shading options for windows. These periods are calculated differently if they are outdoor spaces or buildings. Non-building outdoor shade requirements are better defined by the environmental variables that affect thermal comfort or thermal stress (temperature, radiation, air velocity, relative humidity), while the building shade period is better defined by the heating and cooling requirements of the building or by indoor thermal

comfort. These are also affected by environmental variables, but affected by the building. Outdoor spaces and buildings do not have the same shading periods.

There are several methods to determine the overheated period in buildings. Reinhart (2014) describes a solstice method, a degree day method, and a thermal balance method. The author uses similar methods but instead of the solstice method an outdoor temperature method is used. The goal of all of these is to predict when shade will be needed to reduce solar gains to the building, reducing cooling loads and overheating. This period will be defined by a start and end date and a start and an end hour. The timetable plot of bioclimatic needs proposed by Olgyay can be used to show these in one single chart. Static devices will always be symmetrical around the summer solstice but unfortunately, temperature will not. A fixed shade will probably provide excessive or insufficient shade during some part of the year.

a. *Exterior Temperature Method:* When the method is based on exterior temperature, the overheated and under-heated periods are determined using the outdoor dry bulb temperature and its relationship to a reference temperature which is usually linked to the balance point temperature, the temperature at which a building needs neither heating nor cooling for comfort because the internal gains equal the internal losses. The assumption is that when outdoor temperature is above the reference temperature the building will overheat and need air conditioning to maintain comfort. Shade during this period would reduce cooling loads in mechanically conditioned buildings and improve comfort in naturally ventilated buildings. This method is very easy to implement but it does not consider different types of buildings with differing envelopes and heat capacities, or different schedules and internal loads. Thus, this method is more effective when implemented to shade on light weight buildings or for exterior spaces.

   The Olgyay brothers proposed a reference balance point of 21.1°C in temperate areas, and higher in buildings closer to the equator (Olgyay, 1963). They plotted this overheated period in a matrix divided in hours and months, which they called the timetable plot of bioclimatic needs. This value is now much lower than 21°C in contemporary buildings with better envelopes. The method, however, can still be implemented using a different value and Climate Consultant provides a very easy to use tool to implement it with a sun-shading chart. This chart shows every hour of the year divided in two six-month periods, from December 21 to June 21 and from June 21 to December 21. It provides the position of the sun and shade requirements for every hour of the year based on the outdoor temperature at that moment. Every hour of the year is divided into one of three options: (1) warm/hot (shade needed), (2) comfort (shade helps), and (3) cool/cold (sun needed) according to the comfort model selected. It is then possible to use this sun-shading chart to define the months and the hours within which shade is required. The disadvantage is that the hours are classified based on the comfort model and not on the building properties.

b. *The Degree Day Method:* Degree day method uses heating and cooling degree days (DDs) to determine overheated periods. Heating and cooling degree days based on balance point temperatures provide an estimation of heating and cooling requirements in a specific climate. Heating degree days (HDDs) describe the average daily temperatures below a base temperature. Traditionally, HDDs in the United States were based on 65°F using badly insulated buildings with low internal gains as a reference. As building envelopes have improved, tables for DDs based on 55°F or 50°F have been developed. Cooling degree days (CDDs) for a specified base temperature describe the average daily temperatures above a base temperature. The base temperature for HDD calculations is typically the lower limit of the balance point temperature and the base temperature for CDD calculations is typically the upper limit. In between these two

values, the building will typically not need mechanical heating or cooling. Monthly heating and cooling degree days are plotted for the whole year using degree day tables, or online sources of data. In climates that need both heating and cooling there will be one or more months in the spring and fall in which there will be both heating and cooling. The overheated period starts when cooling degree days are larger than zero in spring and ends when they reach zero in the fall. The designer may decide to define a shorter shade period based on other considerations such as daylight, unequal distribution of CDDs around the solstices, interior blinds, or costs. Climates with high CDDs all year also require shading during the whole year.

c. *The Thermal Balance Method:* The thermal balance method is more precise but requires energy-modeling software to determine cooling and heating loads. It provides more precision than the balance point method because it accounts for the specific properties of the building being analyzed that are not accounted for in the degree day method. Annual building analysis using a local weather file and an approximation of the building, or even simplified as an unshaded box with envelope and internal loads similar to those of the project will provide a monthly bar chart of heating and cooling energy to determine cut off months for the shading system. These energy values can also be converted to carbon emissions using appropriate factors, allowing to compare effects from different sources in a common unit of measure: CO_2e.

2. *Solar Study:* Façade solar studies permit to quickly determine critical orientations that require more solar protection. Solar studies should be done for the overheated period using one of the methods previously described. Values can be expressed as average daily numbers per unit of area or total values for the analysis period per unit area. Shade can be proposed and tested to determine the percentage reduction of solar gains implementing these strategies. This number can be illustrated numerically or graphically. It is always helpful to show a percentage, the reduction in solar gain during that period. Solar gains during peak cooling loads are also helpful. There are several software that perform solar studies such as IESve and Diva.
3. *Shade Design:* The next step is to design shade based on orientation, dimensions of the openings or surfaces requiring shade, and seasonal requirements. Vertical and horizontal shadow angles should be calculated using one of the several methods (e.g., shadow masks) explained in Chapter 7. Shadow masks are very useful because they show annual shading for a whole year in one image. Climate Consultant permits to calculate vertical and horizontal shadow angles using outdoor temperature. Ecotect has been phased out, but had a useful shadow mask tools that included solar radiation. Multiple options can be designed and dimensioned as explained in Chapter 7 using vertical and horizontal shade angles with Equations 7.5 and 7.6. Alternatively, visual trial and error with a 3D modeling tool or a parametric method can be used to determine optimum dimensions.
4. *Performance Evaluation:* The proposal should have lower carbon emissions and energy consumption compared to an unshaded option. It should also provide sufficient daylight. Shading options should be tested for overall energy consumption, illuminance, and luminance levels. A simple shoebox-modeling tool such as Comfen is a quick and easy way to do this, as are other tools that use Energy Plus. A physical model can also be used for daylight studies and a heliodon for shadow studies in analog models. If there are no tools available to calculate energy use and daylight, a comparison of the solar gains on the façade with and without shade is useful. The façade with the least amount of incident radiation on the envelope during the overheated period is the most effective option.
5. *Final Solution or Return to Adjustment:* If the design does not provide sufficient shade or it provides too much shade, it must be redesigned and reevaluated, going back to step 3 assuming the overheated period is correctly calculated.

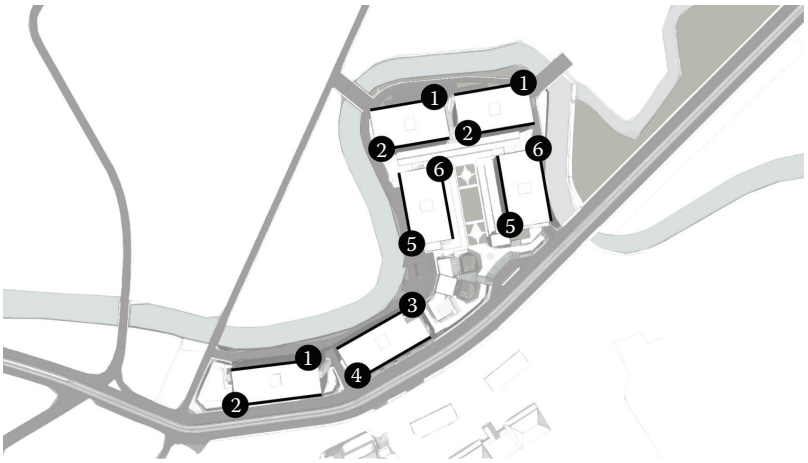


FIGURE 11.13 Typical building façade orientations. (Courtesy of CallisonRTKL.)

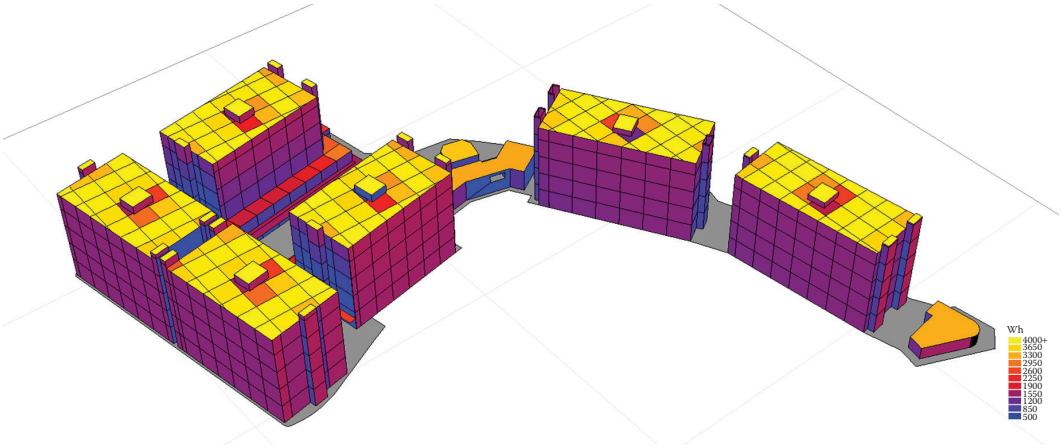


FIGURE 11.14 Solar radiation on facades. (Courtesy of CallisonRTKL.)

The following example illustrates this workflow through is an office building project in Philippines. Climate analysis indicated that it is always warm with temperatures above the balance point, so that cooling was always required, and shading helped reduce solar gains. The first step was to determine typical orientations and minimize the number of options to be studied, six in this case (Figure 11.13). Solar radiation was analyzed for the whole year to determine critical facades (Figure 11.14). Different shading solutions were proposed for the six cases.

For example, even at this equatorial latitude, façade 1, with a more northern orientation, slightly to the west benefits with a vertical shading system (Figure 11.15) while a horizontal shading system is better for façade 2 oriented closer to the south (Figure 11.16). The overhangs are calculated using the sun path diagram in climate consultant, with the method explained in Chapter 7. It is important to calculate and propose vertical and horizontal shading angles since these provide more flexibility than fixed dimensions and multiple options can be designed that respond to these angles. Shading dimensions can be generated from vertical and shadow angles as a function of the window dimensions. Figure 11.17 shows an option that responds to the proposed vertical shadow angle. Figures 11.18 through 11.20 show insolation analysis of several options. The first option receives

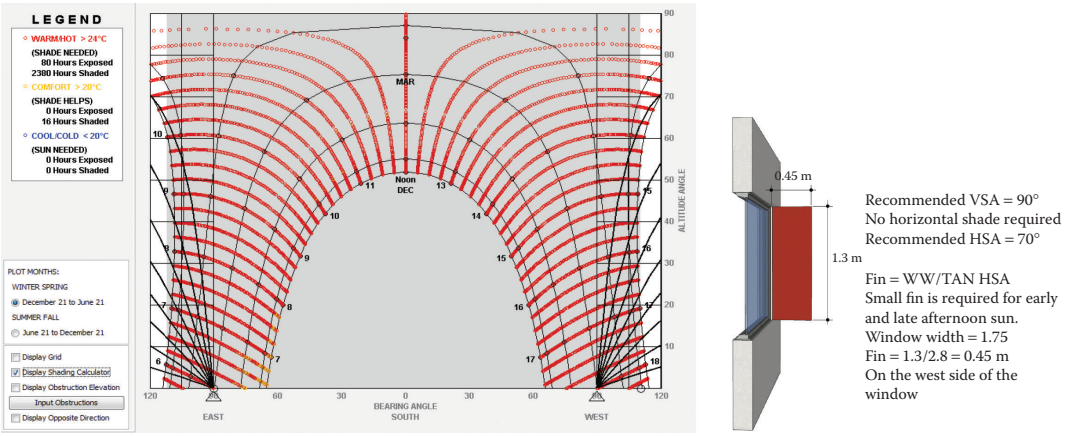


FIGURE 11.15 Shadow angle calculation in Façade 1. (Courtesy of CallisonRTKL.)

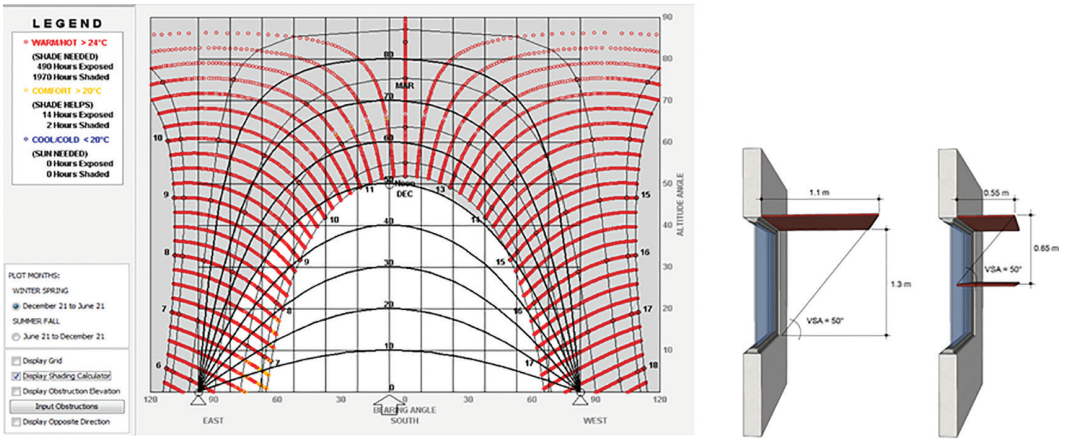


FIGURE 11.16 Shadow angle calculation in Façade 2. (Courtesy of CallisonRTKL.)

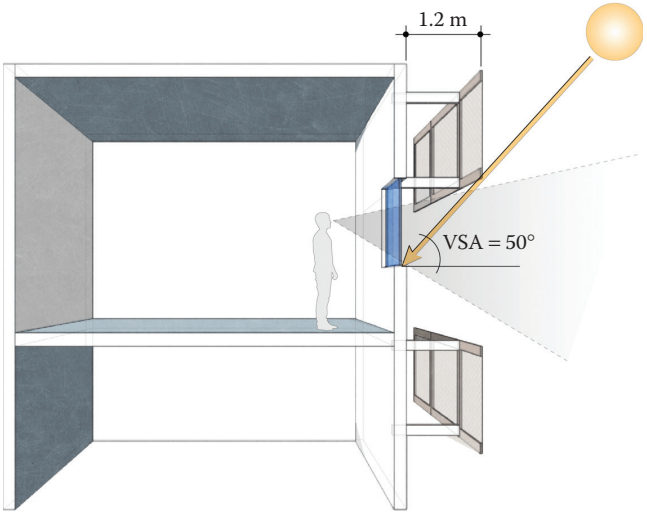


FIGURE 11.17 Shade system that responds to vertical shadow angle. (Courtesy of CallisonRTKL.)

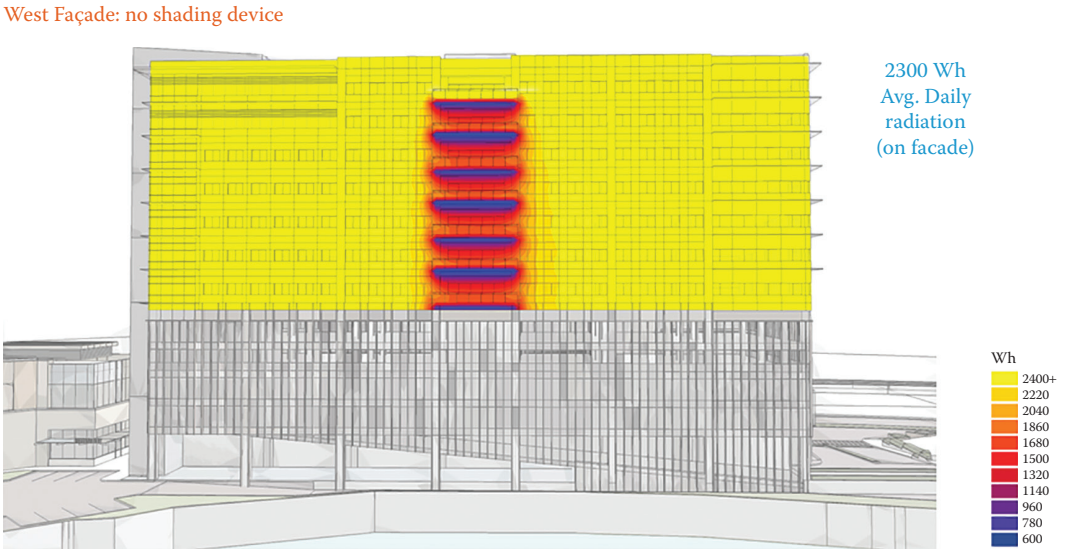


FIGURE 11.18 Solar analysis on West Façade without shading. (Courtesy of CallisonRTKL.)

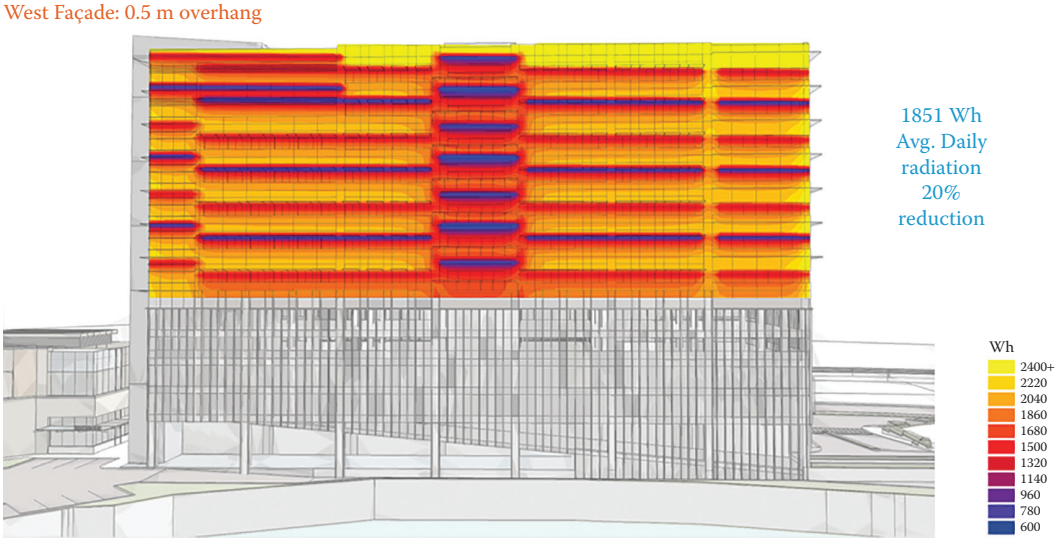


FIGURE 11.19 Solar analysis on West Façade with 0.5 m overhang. (Courtesy of CallisonRTKL.)

about 2.3 kWh/m^2, adding a simple overhang reduces gains by about 20% to 1.85 kWh/m^2 adding the proposal reduces average daily gains to 1.4 kWh/m^2 or a reduction of about 41% in incident solar radiation on the façade. Values are daily averages using data for the whole year. Clearly the last option, optimized with the vertical shadow angle is most effective in reducing the amount of incident solar radiation on the façade. Even though this analysis provides an incomplete picture of energy consumption, it helps to provide an understanding of solar gains on the façade and performance of shading strategies, which can be an important portion of total energy consumption in a hot climate. This is especially important in a place like the Philippines where walls are not

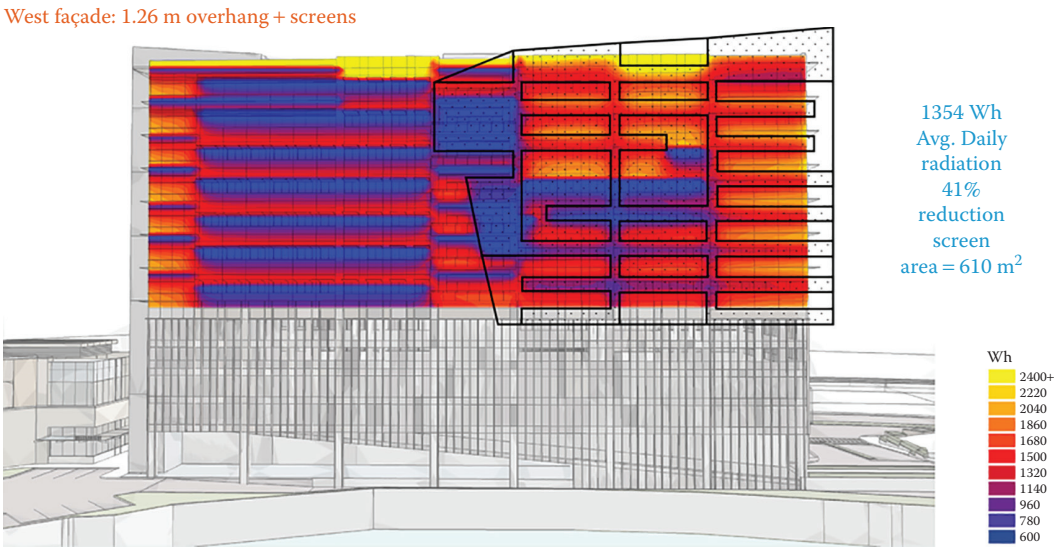


FIGURE 11.20 Solar analysis on West Façade with overhang and shading proposal. (Courtesy of CallisonRTKL.)

insulated and glass is not high performance, so solar gains are a larger percentage of total loads. In this climate, any solar gain in the space will have a negative effect on thermal comfort and cooling loads (Figure 11.21).

A project in Vanke City, Xi'an illustrates how a solar study can help to understand facade priorities. Climate analysis indicates that the warmest period is from June 1 to August 31. Figures 11.22 and 11.23 show a typical day during the warmest period in the year and Figures 11.24 and 11.25 during the winter period from December 1 to March 31. Figure 11.26 shows average daily data for summer and winter in each façade, helping to pinpoint critical facades each season. In the summer,

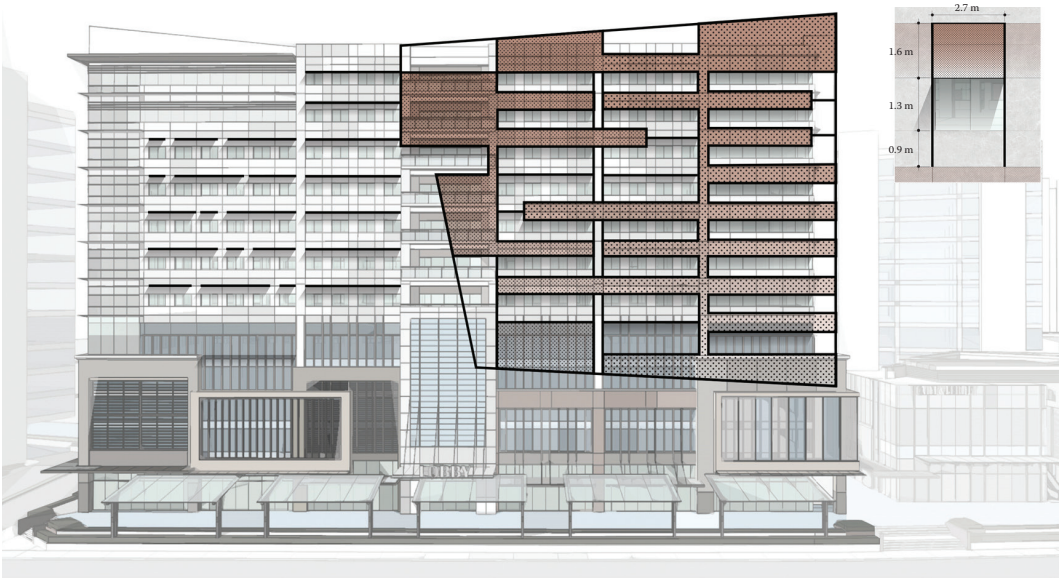


FIGURE 11.21 Proposed shade system. (Courtesy of CallisonRTKL.)

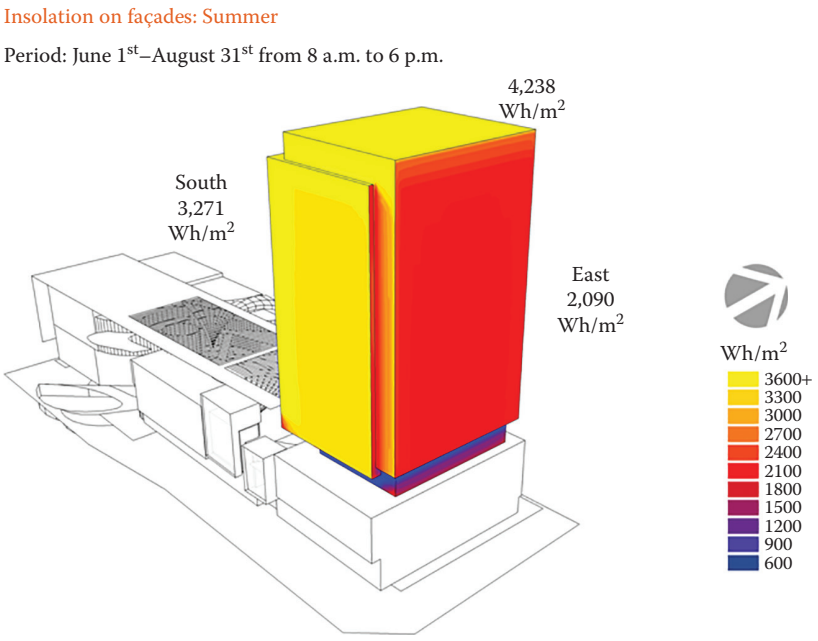


FIGURE 11.22 Summer solar analysis Vanke office. View from the southeast. (Courtesy of CallisonRTKL.)

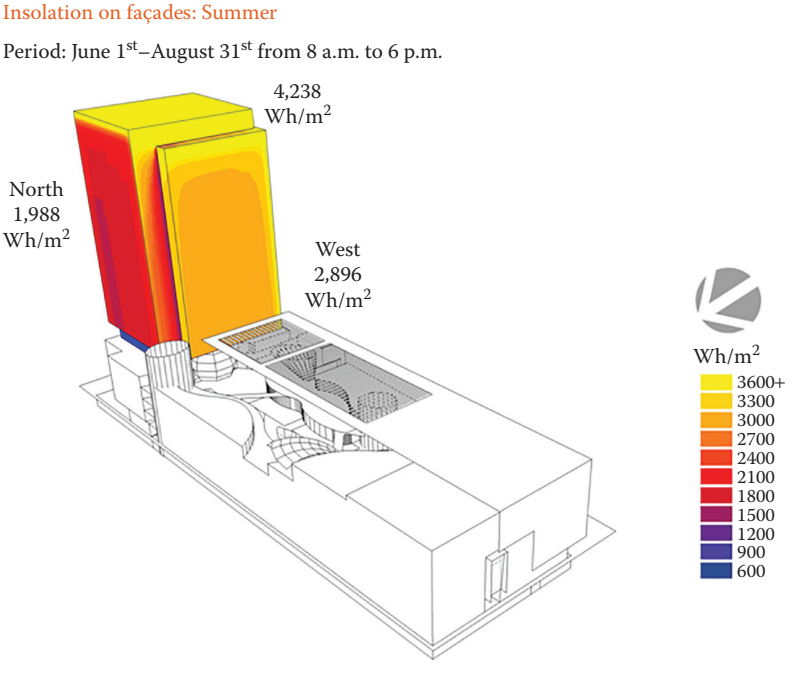


FIGURE 11.23 Summer solar analysis Vanke office. View from the southeast. (Courtesy of CallisonRTKL.)

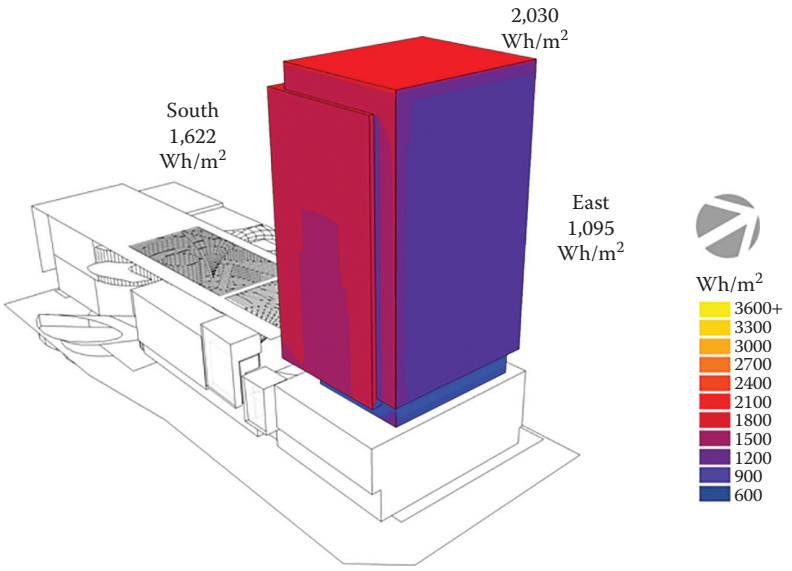


FIGURE 11.24 Winter solar analysis Vanke office. View from the southeast. (Courtesy of CallisonRTKL.)

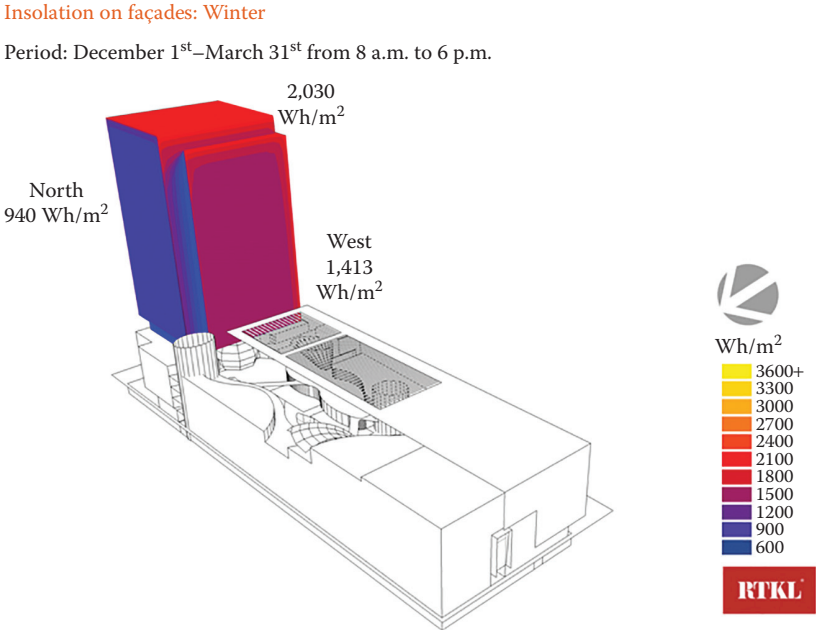
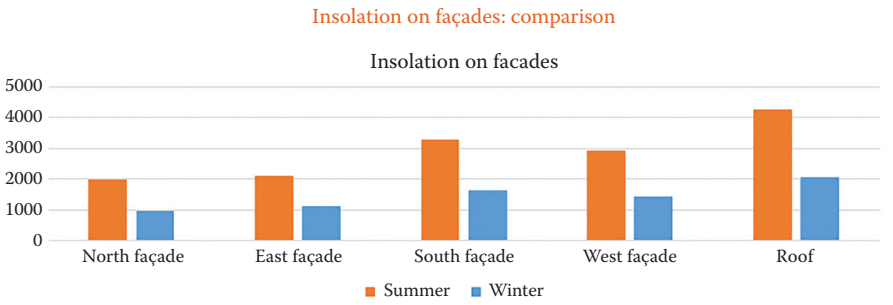


FIGURE 11.25 Winter solar analysis Vanke office. View from the northwest. (Courtesy of CallisonRTKL.)



Summer:
Roof receives most solar radiation. Most critical facade is south followed by west.

Winter:
Heat gain on the facades averages 50% of summer values. Highest value is also on the roof but followed very closely by the south and then the west facades. Solar heat gain in the winter could be beneficial depending on internal loads. Glare should be controlled.

	AVG. daily radiation (Wh/m^2)	
Surface	Summer	Winter
North façade	1988	940
East façade	2090	1095
South façade	3271	1622
West façade	2898	1413
Roof	4238	2030

FIGURE 11.26 Average daily solar radiation on facades. (Courtesy of CallisonRTKL.)

solar gains will be undesirable, while in the winter they might be desirable. Highest gains in the summer are in the roof followed by the south façade and west façade, making them the most important facades to protect in the summer. The west façade is also more critical because of the higher temperatures in the afternoon which also increase heat flows by conduction. The south façade provides the most passive heating in the winter. Even though the definitions of these periods did not consider the building's actual conditions, they provide an indication of solar incidence during critical periods of equal length.

A temporal map solar study can be used to compare incident solar gains in a façade or parts of the façade (e.g., windows) to determine shading performance as a function of the reduction of solar gains (Figure 11.27). These images show insolation directly on the façade but there are other simulation options that show the data in a different way. A common form is to use a matrix that includes all hours and months to graphically show incident solar radiation during all hours of the year. These are commonly used to analyze a portion of the building such as a window or a wall but they can

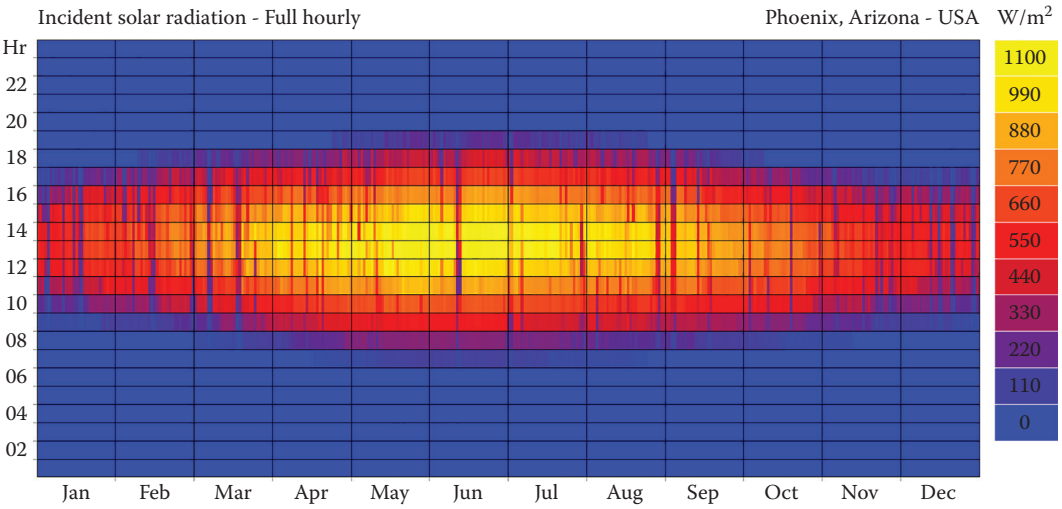


FIGURE 11.27 Annual solar gains for a horizontal surface in Phoenix.

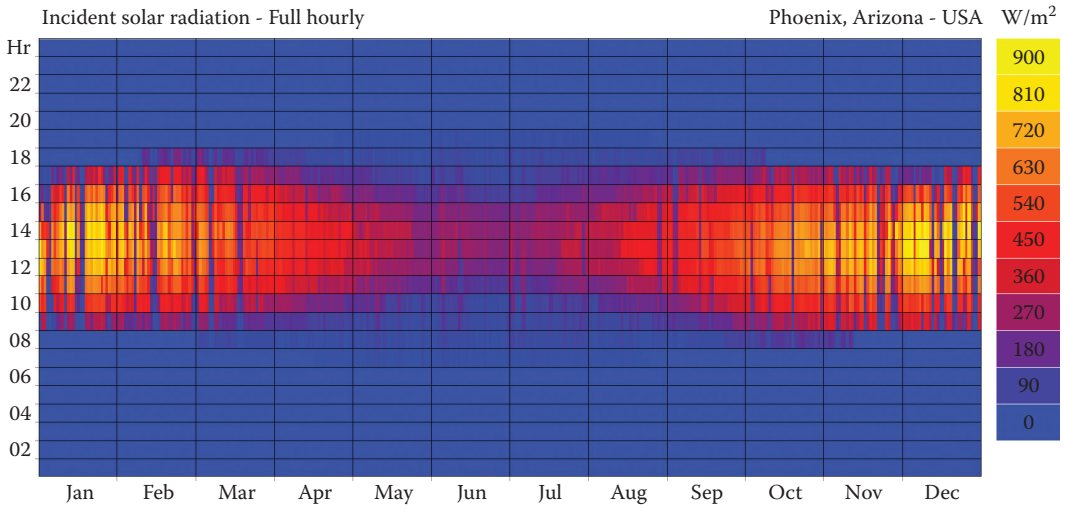


FIGURE 11.28 Annual solar gains for a south-facing surface in Phoenix.

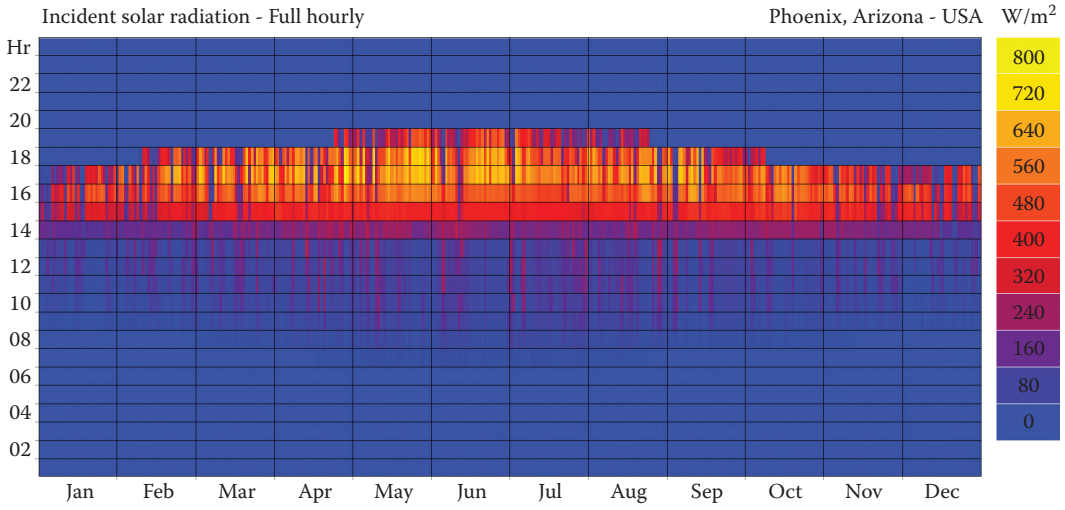


FIGURE 11.29 Annual solar gains for a west-facing surface in Phoenix.

also be used to analyze all surfaces in a building to study self-shading and determine most effective massing. Figures 11.28, 11.29 and 11.30 show incident solar radiation on a roof and south and west facades using Ecotect's solar exposure full hourly calculation. Differences in the quantities and the hours in which these surfaces receive solar radiation are immediately apparent.

Shadow masks are good indicators of shading system performance. Climate Consultant permits to calculate vertical and horizontal shadow angles indicating the number of hours during which shade is provided above a certain temperature. Ecotect, which is being phased out by Autodesk, has a useful shadow mask tool that shows results as percentage shade or solar radiation blocked. Shadow masks are useful because they show in one single image, performance for every hour and every day of the year. However, they only show this for one specific orientation at a time.

For the Tainan library competition with Sheng-ping Lin, Yuwen Peng and Arianne Ponce, the first step in the design of the envelope system was to study incident solar radiation in all facades (Figure 11.30). A shade system was proposed, comprised of square perforations with different

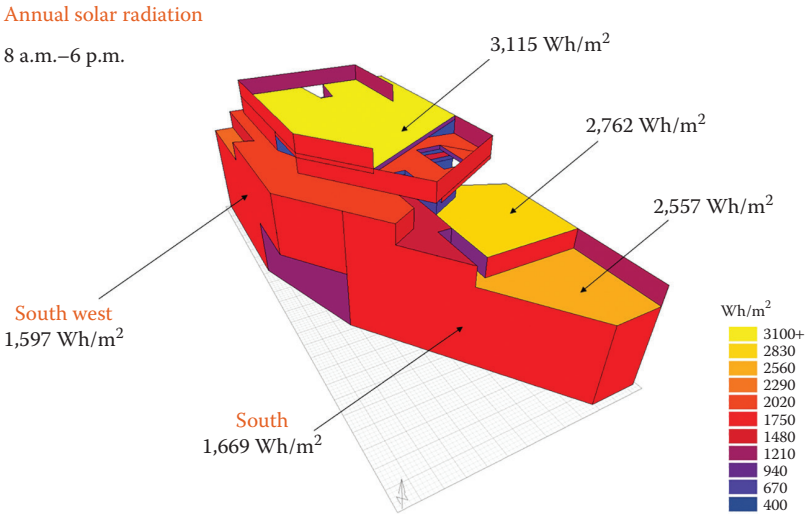


FIGURE 11.30 Annual envelope solar gains for Tainan Library proposal.

proportions and horizontal and vertical elements that extend differently according to the orientation and dimensions of the openings (Figure 11.31). This system would cover much of the façade and could be built with the clay commonly used in local architecture. Based on the solar study, four reference orientations (A,B,C,D) were studied to determine optimum dimensions of these elements (Figure 11.32). Figure 11.33 shows the calculations for one of these orientations using Ecotect's solar tool. In some areas the façade works as a simple ventilated double skin and the size of the perforations is adjusted for views and daylight (Figure 11.34). Figure 11.35 shows a view of the library, with the shading wrapping around.

In a skylight in this warm climate, diffuse daylight is preferred over direct daylight which also brings heat to the interior of the space. Figure 11.36 shows a solar analysis used to design a skylight system and the opacity and transparency of its components. Daylight studies are done inside the space to refine the design of the skylights.

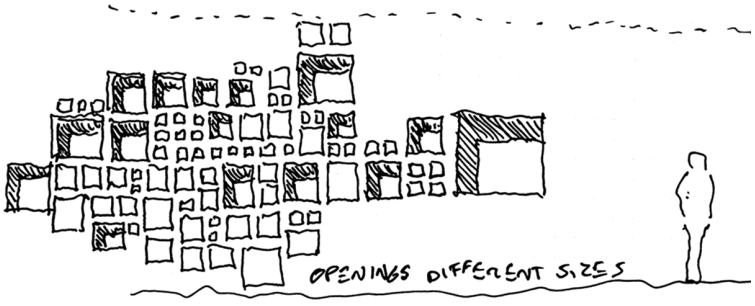


FIGURE 11.31 Shading system concept for Tainan Library competition.

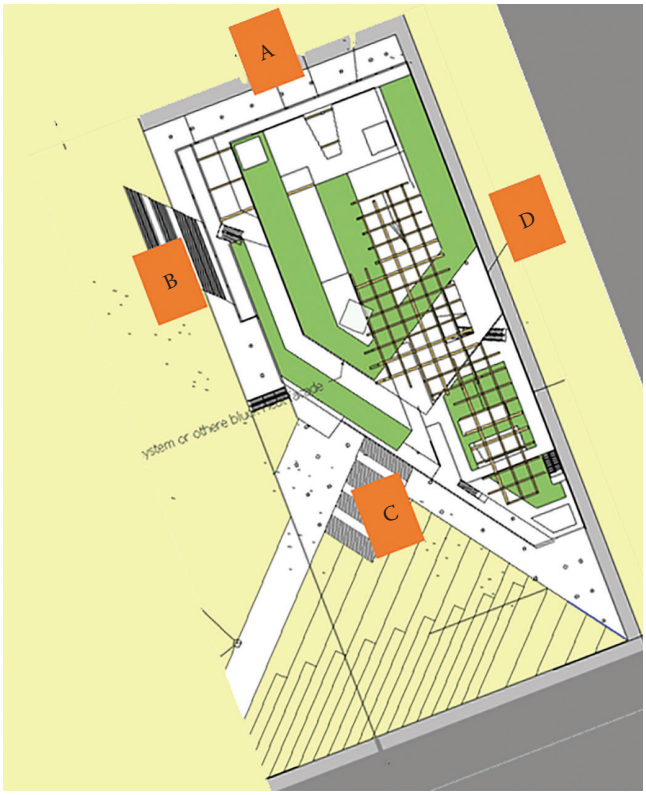
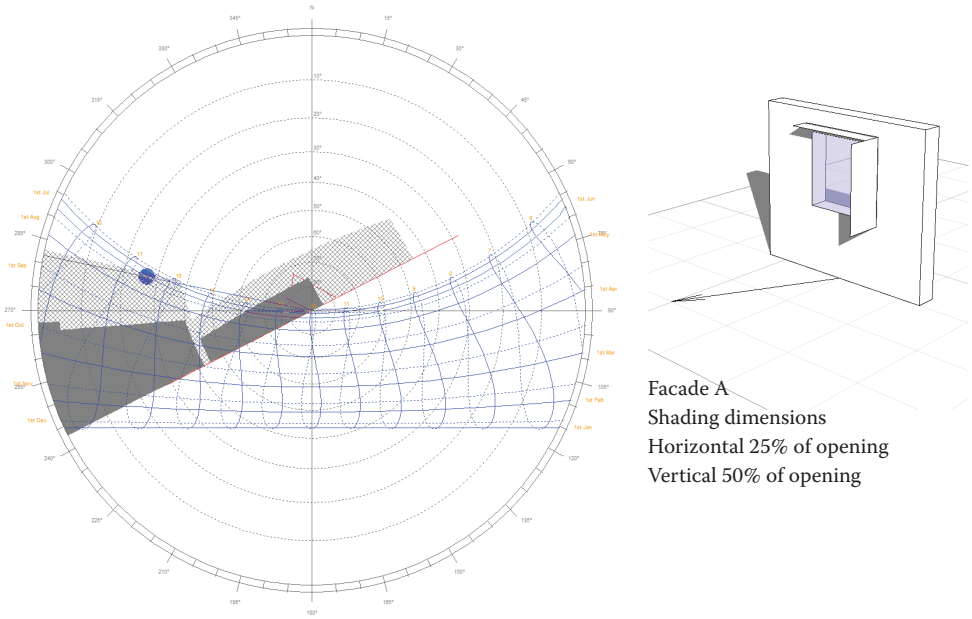


FIGURE 11.32 Different façade types per orientation for Tainan Library competition.



Facade A
Shading dimensions
Horizontal 25% of opening
Vertical 50% of opening

FIGURE 11.33 Horizontal and vertical projection calculations for façade A.

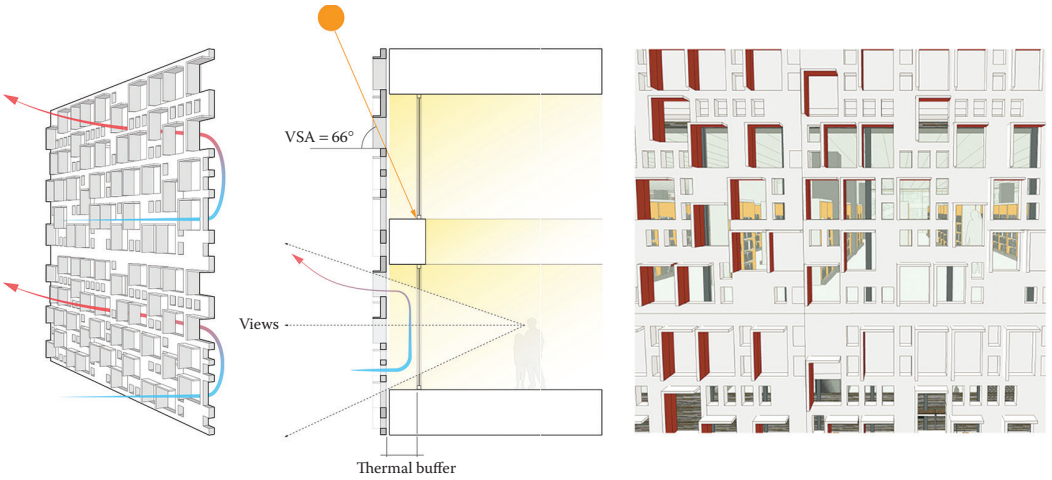


FIGURE 11.34 Shading system concept as a ventilated skin for Tainan Library competition.

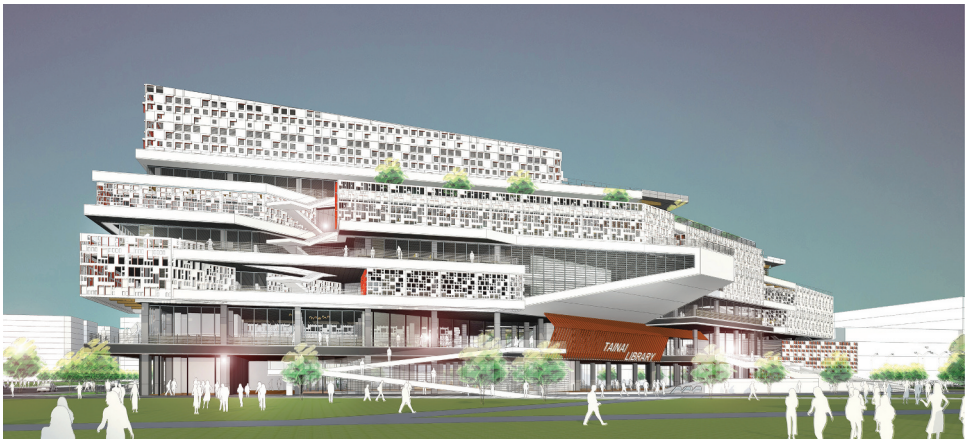


FIGURE 11.35 View of the Tainan Library proposal.

11.5.2 Daylight

Daylighting describes the controlled use of nonelectrical light inside buildings. Daylight buildings provide many benefits, including a reduction in electrical lighting energy, potential for views and enhanced quality of the indoor environment in multiple types of programs such as schools, retail, hospitals, and residential applications. Daylight in a building can be admitted through transparent objects and then reflected or scattered. The goal of daylighting is usually to provide enough quantity for the task and good quality for the occupants while reducing heat gains during the overheated period and all year glare.

There are some basic concepts that are important in all daylight analysis. Luminous flux is the quantity of visible light emitted by a light source. An example is the lumen value indicated in the boxes of light bulbs. A higher lumen value indicates that there is more light coming out of the light bulb. The luminous efficacy is the number of lumens produced by each watt of electrical power used by the source of light. For daylight the source of light is total radiation. Daylight provides more light per unit of energy than any electrical source of light, though LEDs are reaching the same levels of

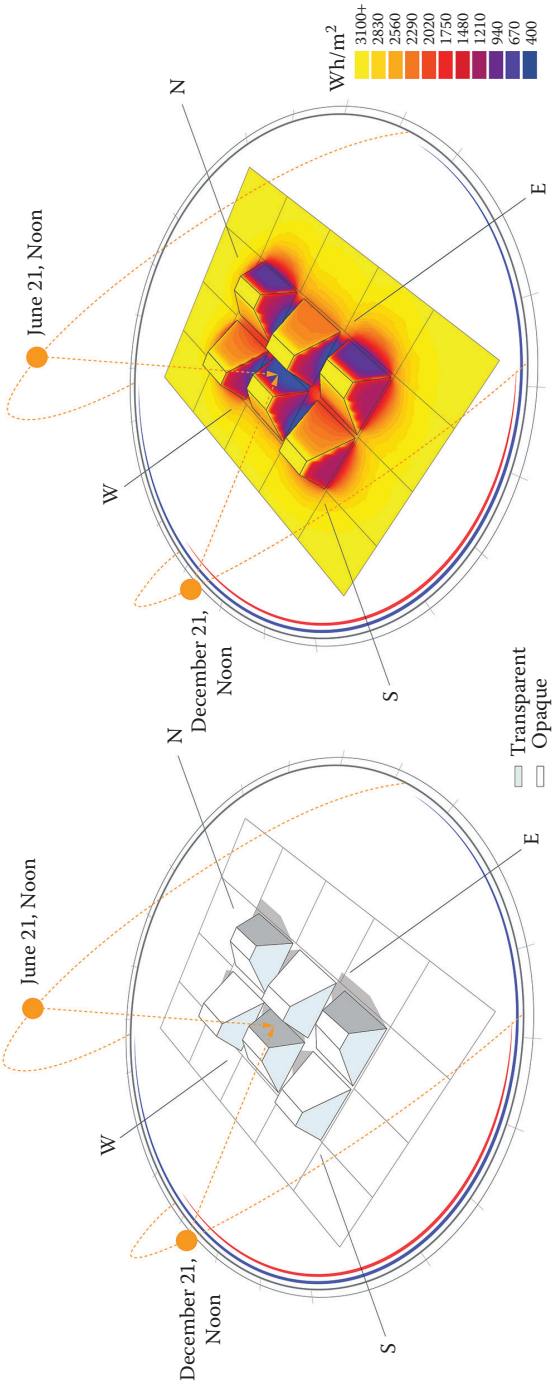


FIGURE 11.36 Tainan library skylight analysis.

efficiency. Diffuse daylight has a higher luminous efficacy than direct light because it provides more light per unit of heat than direct light. It is possible to reduce electrical loads during peak cooling periods in which there is also more daylight availability. Direct light also is more prone to generate glare than diffuse light. Illuminance describes the total luminance flux incident on a given surface and is measured in lumen per unit area. A lux describes the amount of lumens/m^2. Luminance describes the light that is reflected off or transmitted through a surface in various directions. It measures luminous intensity per surface area or candela/m^2.

Daylight analysis is an area of building simulations through software, in some cases integrated with a CAD tool such as DIVA for Rhinoceros and Sefaira for Sketchup. As mentioned earlier, daylight design typically aims to achieve required illuminance levels, avoid glare, control solar heat gain, and reduce undesirable heat losses through the windows during cooler seasons, all of this while providing visual balance and an enjoyable environment. The daylight area is that part of the building in which there is sufficient daylight to provide the required illuminance levels so that electric lights can be turned off or dimmed. Daylight Autonomy (DA) is a dynamic daylight metric that indicates the percentage of annual daytime hours that a given point in a space is above a specified illuminance level. It was originally proposed by the Association Suisse des Electriciens in 1989 and was later improved by Christoph Reinhart. A common value proposed by the Illuminating Engineering Society of North America is 300 lux, proposed for most workplace environments, including offices and classrooms. sDA_{300} (50%) means that at least 50% of the operating time the illuminance level is above 300 lux. Reinhardt (2014) over the course of a two-year study involving students from several schools of architecture compared predicted daylight autonomy with perceived daylight spaces and found a good correlation between the student assessments and simulation-based daylight availability metrics.

For a large retail project in Qingdao, a coastal city in China there was concern of excessive solar gains from the skylights, which were already under construction, and could not be modified. An interior system was proposed to reduce summer solar gains and reflect light, improving daylight year round. The system proposed consisted of "s" shaped components (Figures 11.37 and 11.38) with horizontal, slightly sloped, elements at the top and bottom that block direct light when the sun is higher up. Light is reflected on the vertical surfaces of the objects, into the space, especially with lower altitude sun. Several tests were done, including simple reflection studies (Figures 11.39 and 11.40), which cannot be used to quantify the amount of radiation or daylight that is reflected but do allow a quick estimation of daylight potential as a function of these reflections. These pendants were placed high and with more density toward the south of the skylight to keep the heat up and close to the skylight. The recommended vertical separation was about twice the height, while the horizontal separation is about two to three times the height, and staggered was better than aligned. The program used for this analysis (Ecotect) assumes that the angle of incidence is equal to the angle of reflection and calculates accordingly as a function of solar azimuth and altitude. Several options with different dimensions, angles, and separations between them were tested (Figure 11.41) and the glass in the skylight was also changed to a low solar heat gain coefficient (SHGC) glass. Even though most of the reduction in solar gain is due to the glazing with a low SHGC, these components added an additional level of fine tuning in the distribution of light with additional aesthetic value. No daylight simulations were done; the reflection tests and solar analysis were considered sufficient (Figure 11.42).

Another example of a daylight analysis is a small shopping mall in Manhattan Beach, California. The project has a central spine with retail on both sides and multiple skylights. However, the daylight quality was not good, sometimes with excessive direct light and glare. The mall owners had to add an interior egg-crate shading system under the skylight to reduce solar grain and glare (Figure 11.43) but this was still not sufficient. The design team was exploring several design options, while the in-house sustainability team provided assistance in the development and evaluation of several schemes (Figure 11.44). These included vertical lowers with different separations and a cloud based shading system. Some of the images from the process are presented.

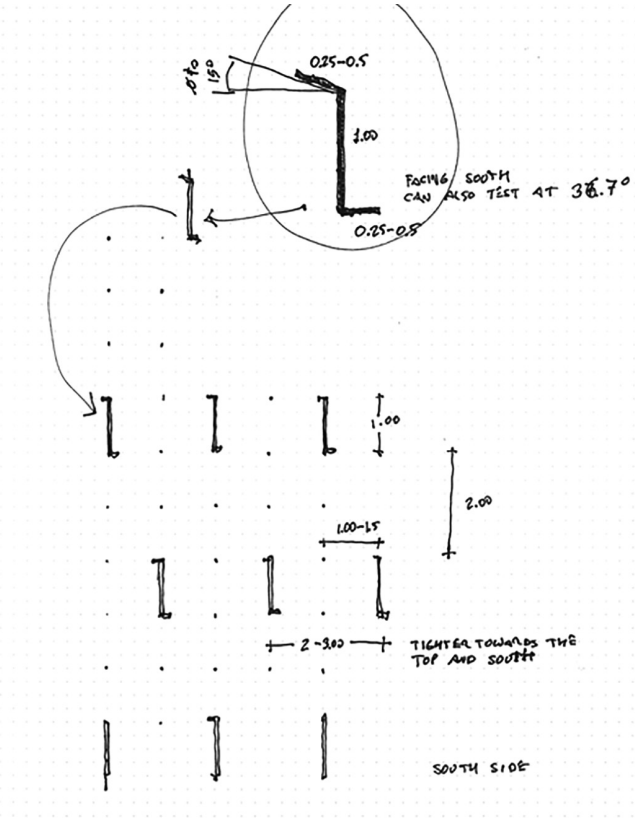


FIGURE 11.37 Initial sketch with design concept with potential separation between pendants.

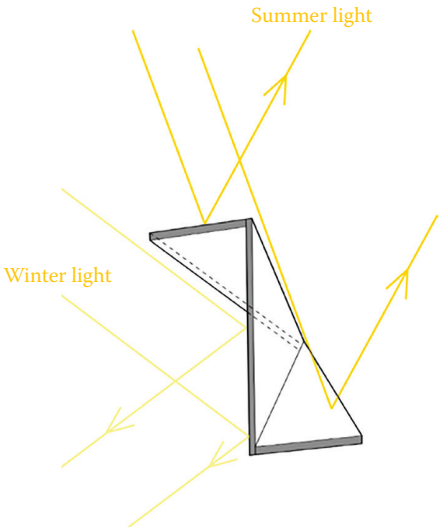


FIGURE 11.38 Basic pendant component. (Courtesy of CallisonRTKL.)

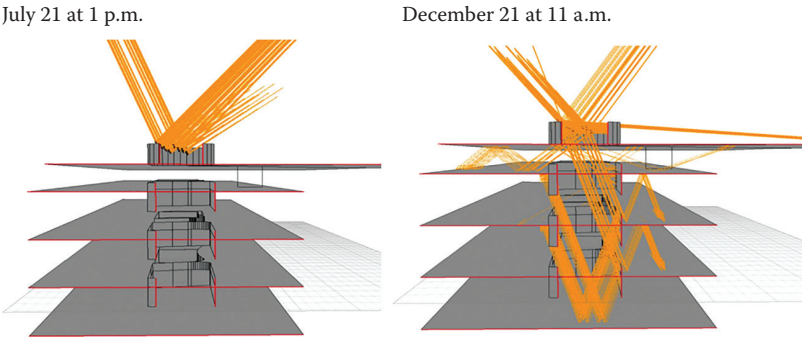


FIGURE 11.39 Reflection study. (Courtesy of CallisonRTKL.)

The first image shows daylight autonomy for the whole mall, comparing two skylight options, one with a visual light transmittance (VLT) value of 0.23 and a SHGC of 0.15 and a second one with a VLT of 0.41 and a SHGC of 0.23 (Figure 11.45). Daylight autonomy is significantly better with a VLT of 0.41. Incident solar radiation was compared between the options with different SHGC (Figure 11.46) to compare reductions in solar gains.

Sefaira, a simulation program, was used to calculate daylight autonomy; however, it has many predefined values (e.g., interior surface reflectivity) which cannot be changed. The results did not show overlit areas during critical periods such as summer noon. IESve was used, and June 21 at noon is shown in Figure 11.47. This was the most critical time and several options were studied; Figure 11.48 shows the proposal compared to on-site measurements on the same date while Figure 11.49 shows illuminance levels in the entrance area on December 21 at noon time.

11.5.3 Outdoor Comfort

The importance of outdoor spaces is increasingly recognized by multiple parties. People enjoy being outside and retail and mixed use projects with outdoor components are becoming increasingly popular, even in locations with very warm or very cold climates where conditions are outside the comfort zone for a large amount of time. If the number of hours in comfort increases, then the occupants can enjoy more time in them, making them more successful.

The environmental and personal factors that affect thermal comfort have already been discussed in Chapter 5. Designers can have more impact on thermal comfort in outdoor spaces because they can modify the air velocity and direction, and the amount of solar radiation in exterior spaces with relative ease. It is common to provide shade during the summer to reduce the effects of solar radiation and to block the wind in the winter. Figure 11.50 includes two photographs of opposite sides of St. Marks square in Venice at the same time on a sunny summer day. One side is in the shade and the other side is exposed to the sun. The temperature, relative humidity, and air velocity are probably very similar; however, the radiant effects are reduced on the shaded side making it more comfortable and popular.

Even though there is specialized software to evaluate outdoor comfort, it is possible to implement a simplified outdoor comfort workflow doing solar and wind studies. Figure 11.51 outlines this process. It is important to understand that this workflow will not predict outdoor comfort; however, by simulating wind and solar conditions, these simulations can be good predictors of the built environments' effect on outdoor comfort.

The first step in the process is to understand the site, especially climate, topography, vegetation, and of course of the buildings around it. In addition to relevant 3D models, it is important to have climate data from the closest possible weather station. Especially important are temperature, relative humidity, direct and diffuse solar radiation and wind direction and velocity. Climate analysis programs such as "Climate Consultant" are used in this first step. As with shading design, a key

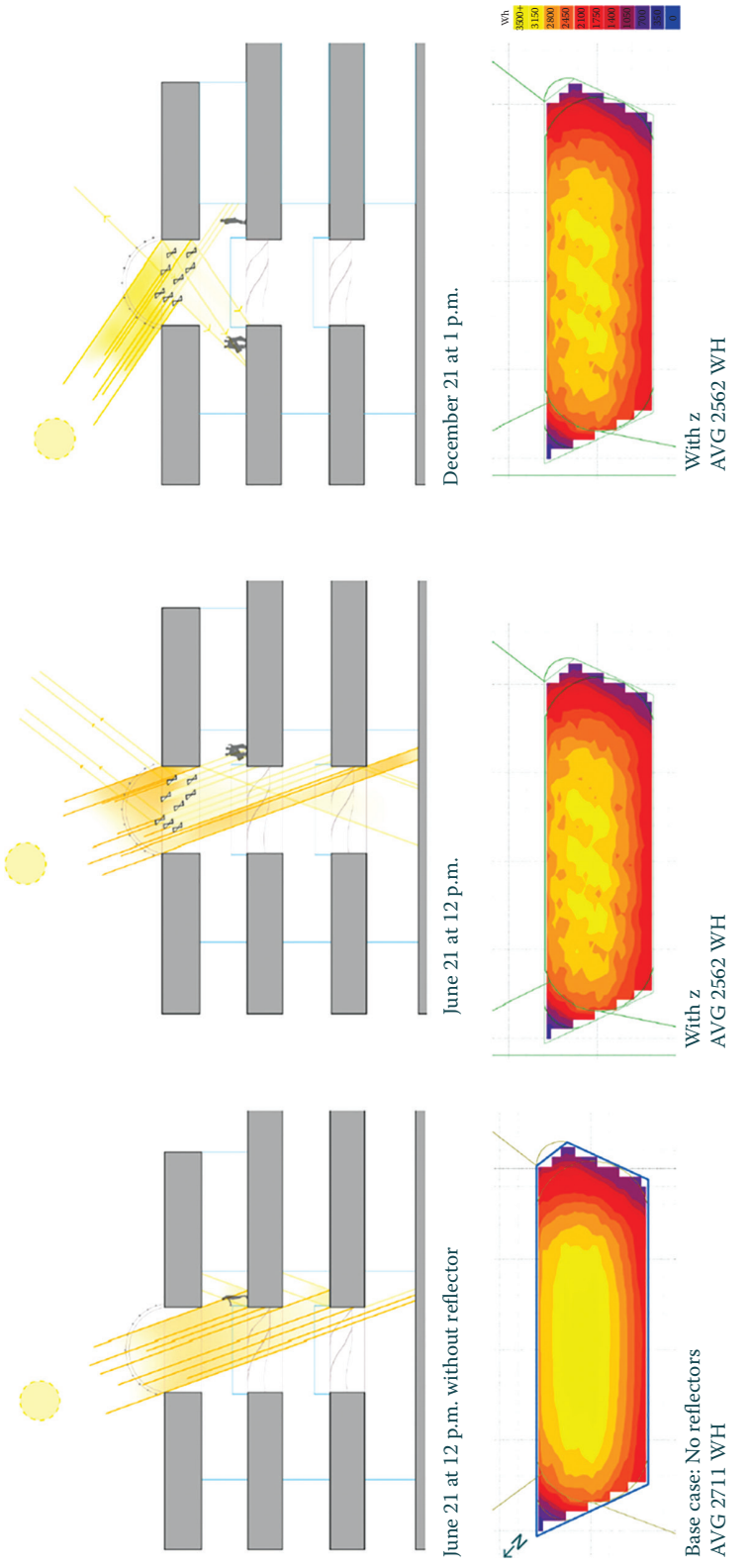


FIGURE 11.40 Comparison of several options. (Courtesy of CallisonRTKL.)

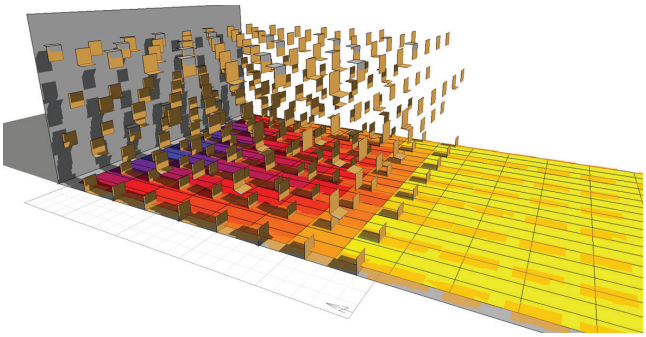


FIGURE 11.41 Solar radiation study. (Courtesy of CallisonRTKL.)

FIGURE 11.42 Rendering artist view of the system. (Courtesy of CallisonRTKL.)

FIGURE 11.43 Egg crate system added to existing skylight.

FIGURE 11.44 Skylight options for Manhattan Beach Mall remodel. (Courtesy of CallisonRTKL.)

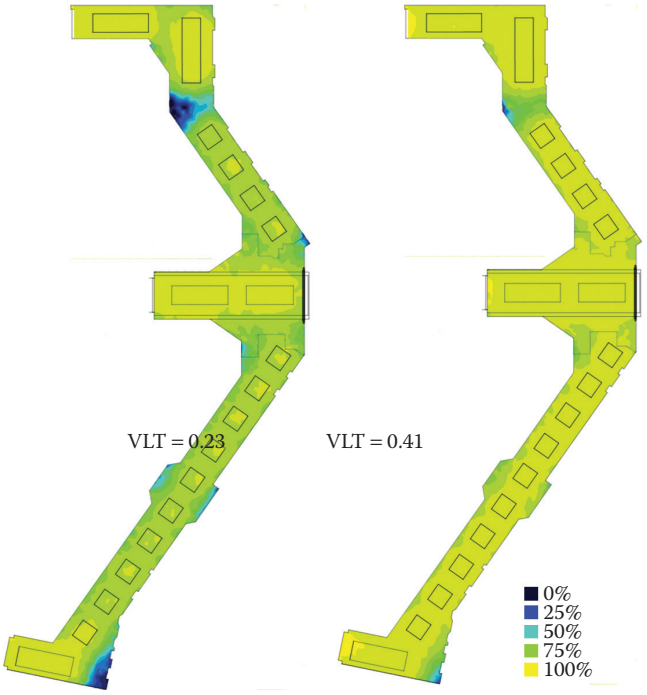


FIGURE 11.45 Daylight study with glass VLT 0.23 and 0.41. (Courtesy of CallisonRTKL.)

component of this climate analysis phase is to determine the overheated and under-heated periods. In this case, these periods are determined as a function of the comfort zone and not the heating and cooling loads in the building. There is no building, the occupant is outside, and for this same reason a larger comfort zone is acceptable. A simple plot of daily averages or a timetable plot with all hours and months can be used, based on a reference temperature or comfort zone. Figure 11.52 shows the temperature range for Cairo, Egypt using airport weather data. When the temperature is above the comfort zone, that period is overheated (indicated as summer in this figure). When the temperature is below the comfort zone, that period is under heated (winter in this figure). Figure 11.53 shows the

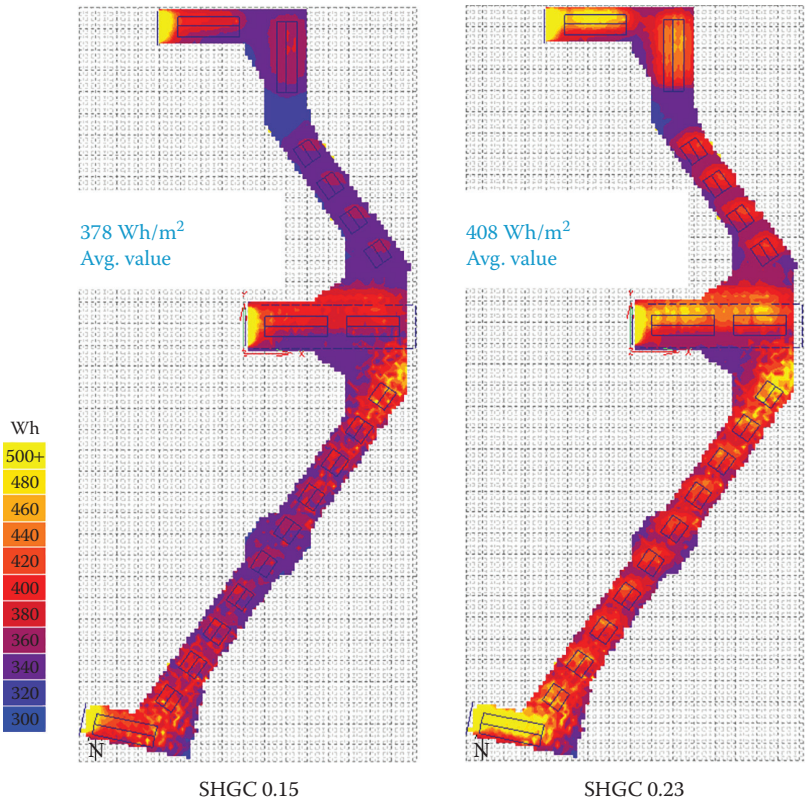


FIGURE 11.46 Solar study with glass SHGC 0.15 and 0.23. (Courtesy of CallisonRTKL.)

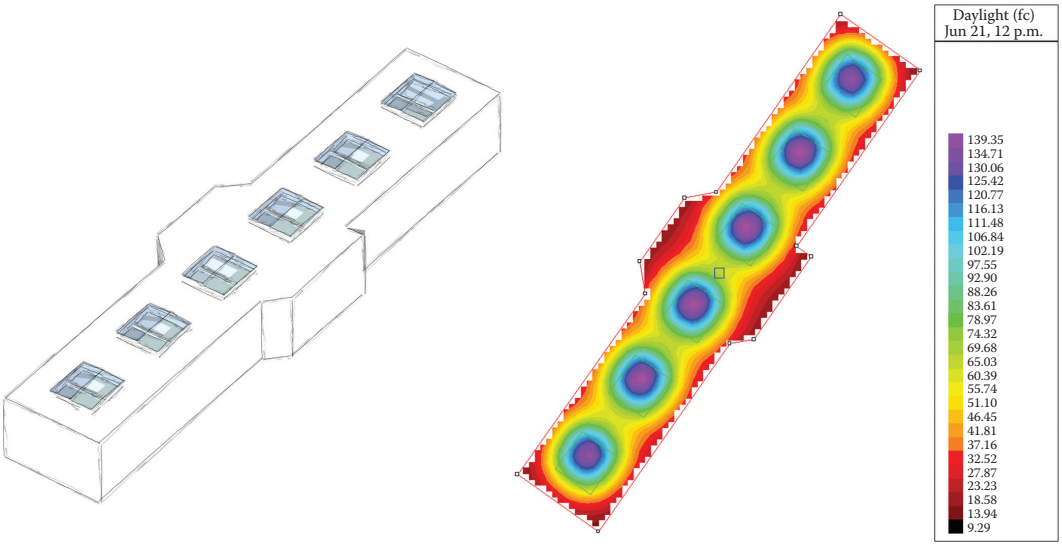


FIGURE 11.47 Illuminance study June 21 at 12 p.m. (Courtesy of CallisonRTKL.)

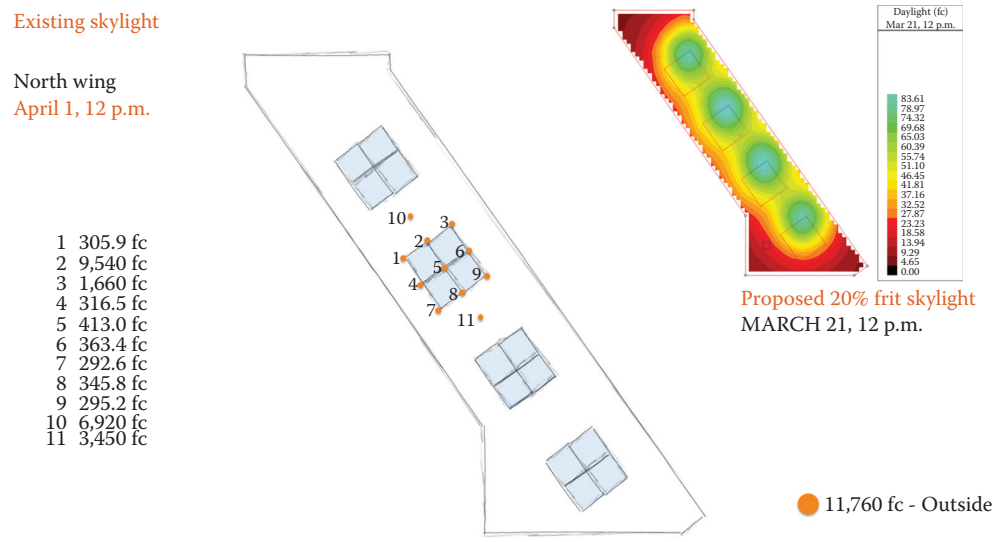


FIGURE 11.48 Illuminance measurements under existing skylight on April 1, 12 p.m. (Courtesy of CallisonRTKL.)

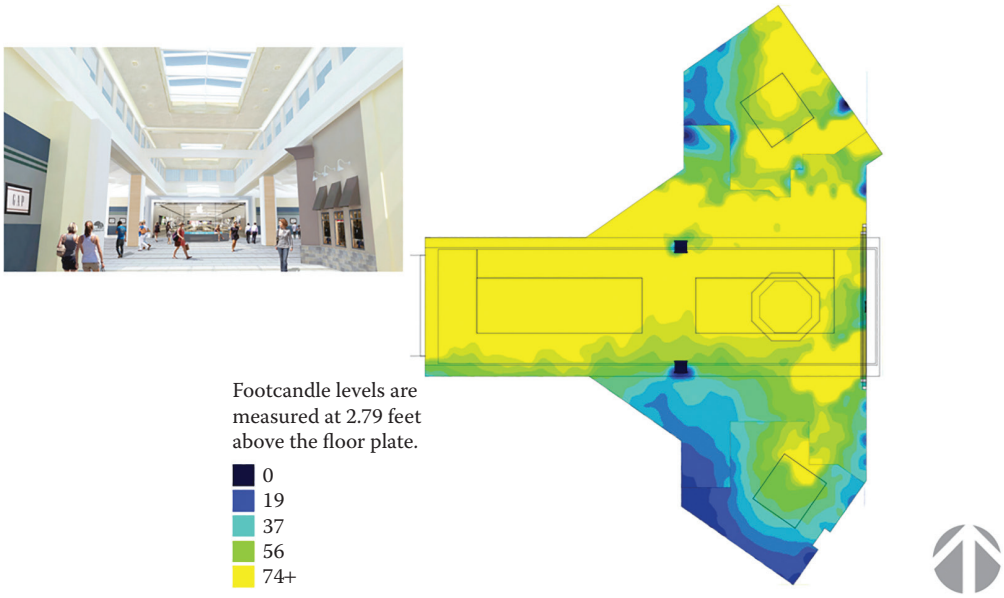


FIGURE 11.49 Illuminance study under entrance area December 21 at 12 p.m. (Courtesy of CallisonRTKL.)

same data but now in a timetable plot of bioclimatic needs. In red are all temperatures above the comfort zone and between 27°C and 38°C, and higher values are in dark red. With this chart, it is now possible to determine the months and hours with temperatures above the comfort zone. Victor Olgyay proposed this method to design shading in buildings (Olgyay, 1963); however, it is probably more effective for outdoor comfort because in this case there is no building envelope that also affects the values. In this case, for example, temperatures are above the upper limit of the comfort zone (27°C) between 10 a.m. and 10 p.m., from May to the end of October.

FIGURE 11.50 St. Marks square in Venice.

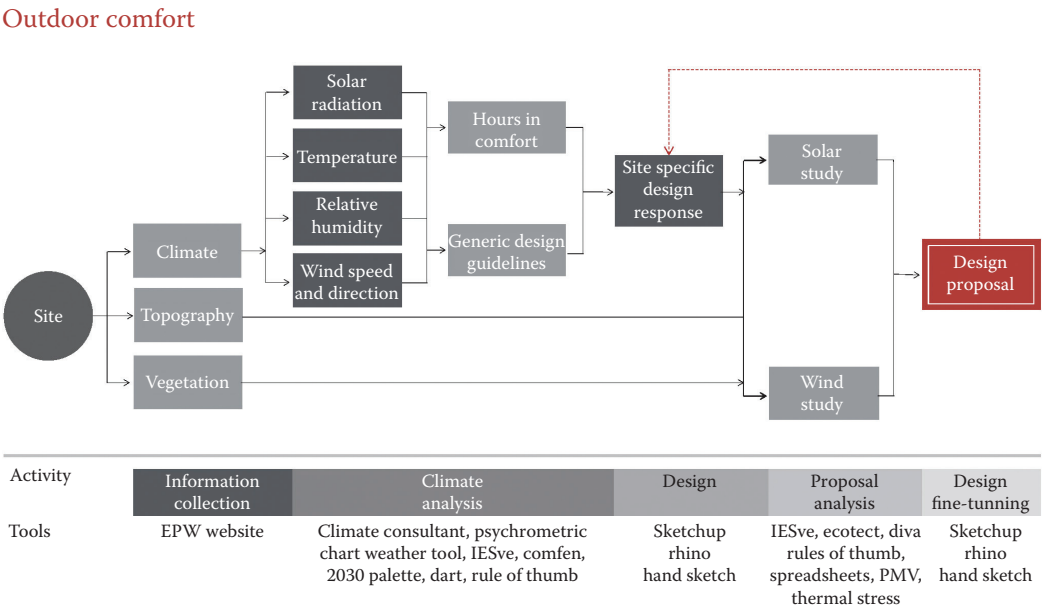


FIGURE 11.51 Simplified outdoor comfort workflow.

Solar and wind studies can be performed after climate analysis is finalized. This analysis shows that shade will be required in outdoor spaces from the end of April to the end of October. It is not necessary to do a detailed comfort study to know that spaces that receive less solar radiation will be more comfortable during this period. A tool such as University of Berkeley's Center for the Built Environment "Thermal Comfort Tool" can be used to calculate actual comfort values. (http://comfort.cbe.berkeley.edu/). This tool helps to predict thermal comfort as a product of the interaction between the environmental and personal variables. To determine the effect of solar radiation using the tool, the mean radiant temperature (MRT) can be increased above the dry-bulb temperature (DBT).

For a project in Guangzhou, China, the process followed similar steps. Figure 11.54 shows a solar analysis during the overheated period, from April 1 to October 31, and from 8 a.m. to 6 p.m. Less solar radiation improves outdoor comfort during this period. Critical areas that receive more solar radiation and which require more shade to provide thermal comfort are indicated. Another image showing the same information but as hours of sun is shown (Figure 11.55). Hours of sun are easier

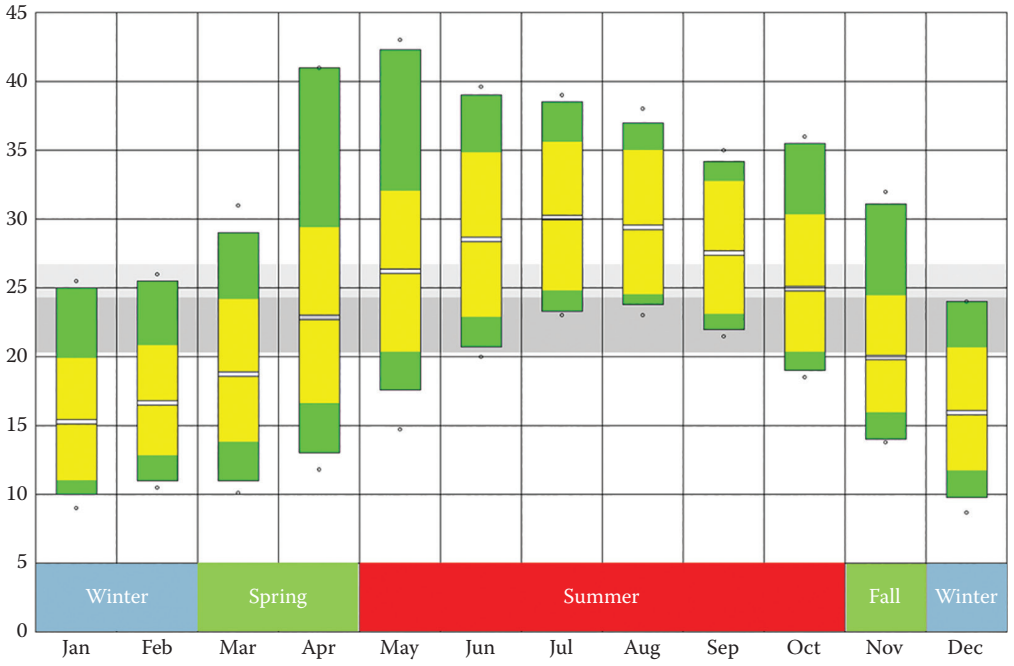


FIGURE 11.52 Temperature range for Cairo, Egypt.

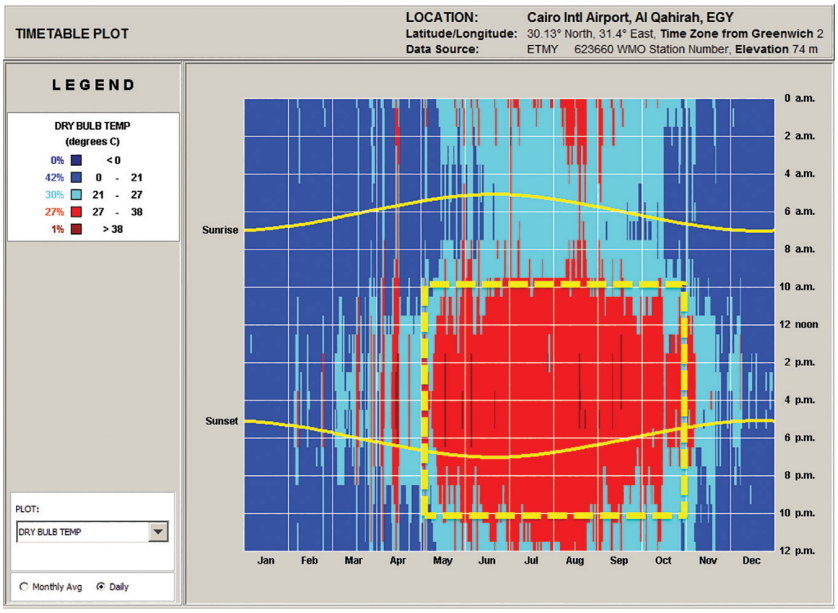


FIGURE 11.53 Timetable of bioclimatic needs for Cairo.

to understand, though not necessarily a good indicator of conditions because the number of hours does not necessarily correlate with the amount of solar radiation, low altitude sun does not provide the same amount of heat as high altitude sun. Wind studies are shown for dominant directions in Figure 11.56. More wind improves comfort in this warm and humid climate. Because of its latitude, solar effects from high altitude sun in the summer are significant, and horizontal shading elements

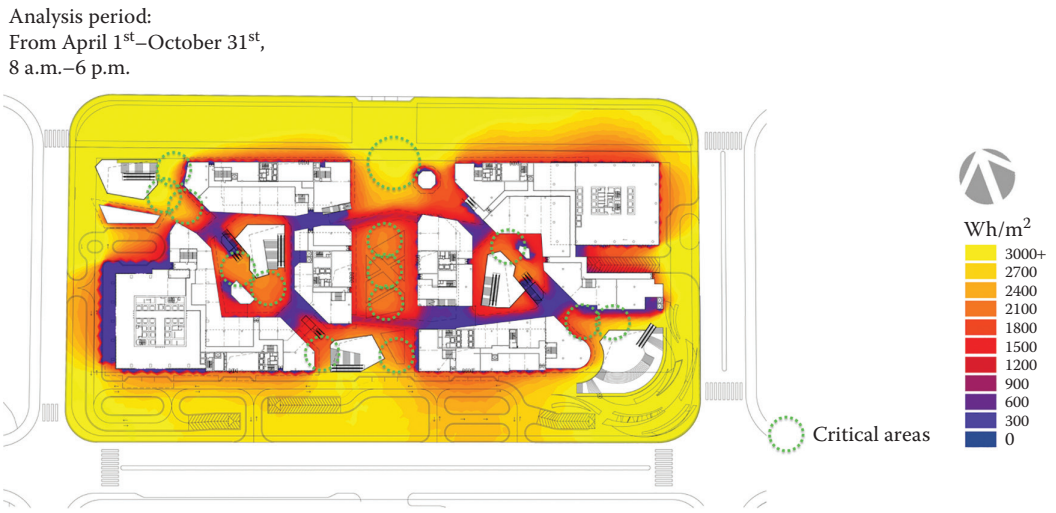


FIGURE 11.54 Solar analysis. (Courtesy of CallisonRTKL.)

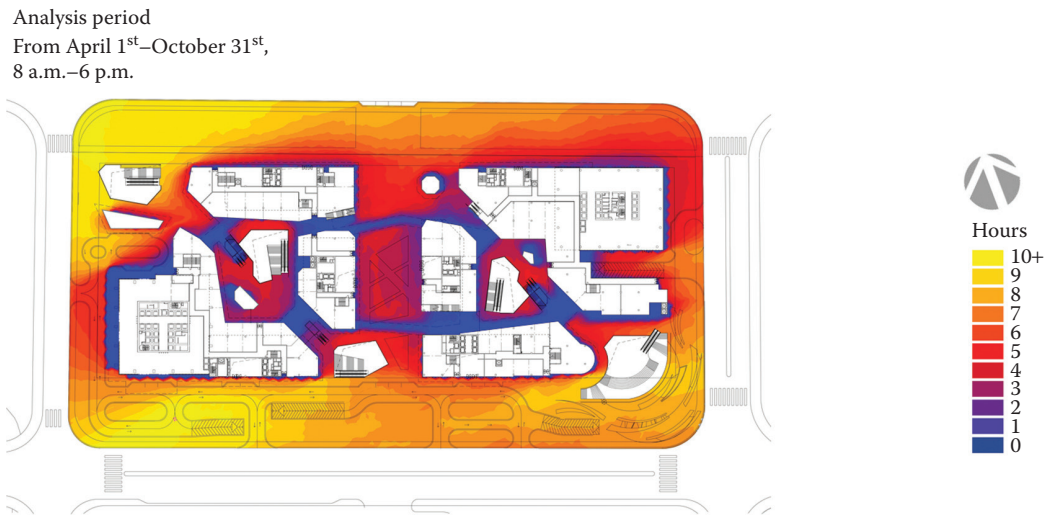


FIGURE 11.55 Hours of sun analysis. (Courtesy of CallisonRTKL.)

are effective in reducing solar radiation. These could also have an aerodynamic form that increases air speed at the ground level to improve comfort. The analysis of wind and solar radiation led to the development of a network of components to improve summer comfort at the ground level, maximizing comfort by blocking the sun and increasing wind velocity. Figure 11.57 shows locations in which shade would improve comfort and locations with potential to capture wind. The overlapping of these two indicates ideal locations for architectural elements that control solar radiation and can increase wind to maximize comfort. Conceptually these are a series of architectural elements at the ground level, proposed to maximize air flow through the body while blocking direct solar radiation (Figure 11.58). The form of these elements would vary depending on their location, always trying to maximize wind and shade. They could provide comfort while also becoming an amenity that could be animated with lights and sound and that could be used as signage and for wayfinding.

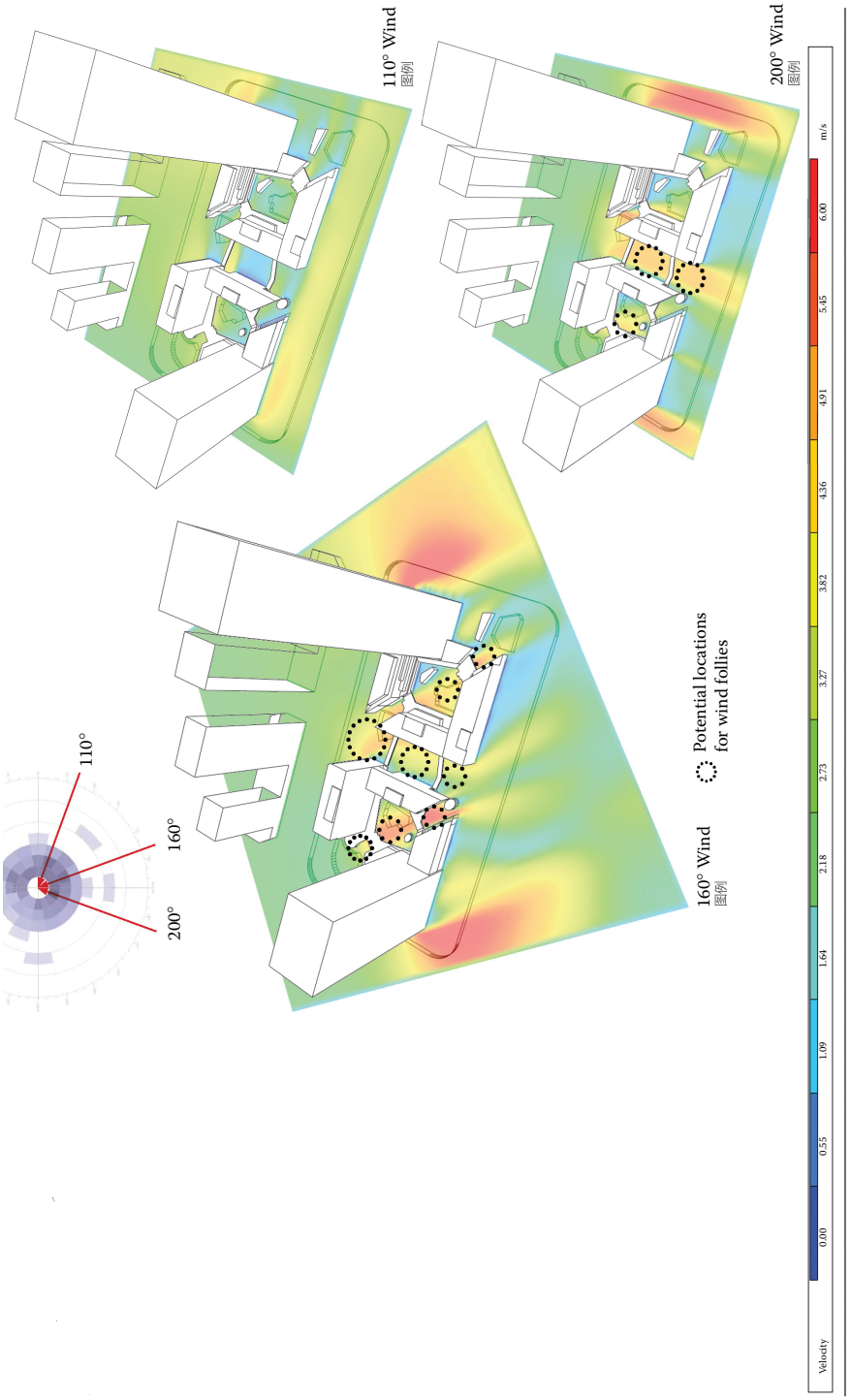


FIGURE 11.56 Dominant wind direction. (Courtesy of CallisonRTKL.)

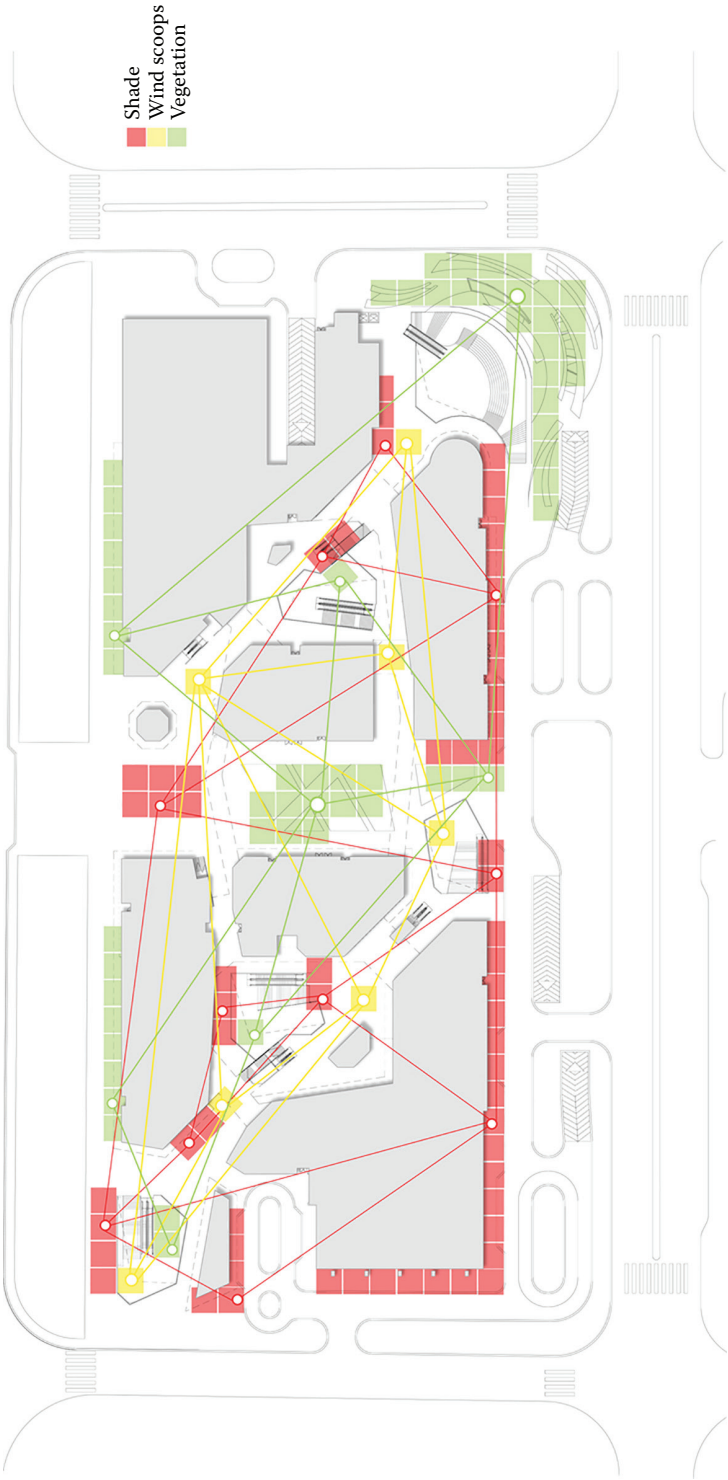


FIGURE 11.57 Solutions generated by overlapping of wind opportunities and solar challenges. (Courtesy of CallisonRTKL.)

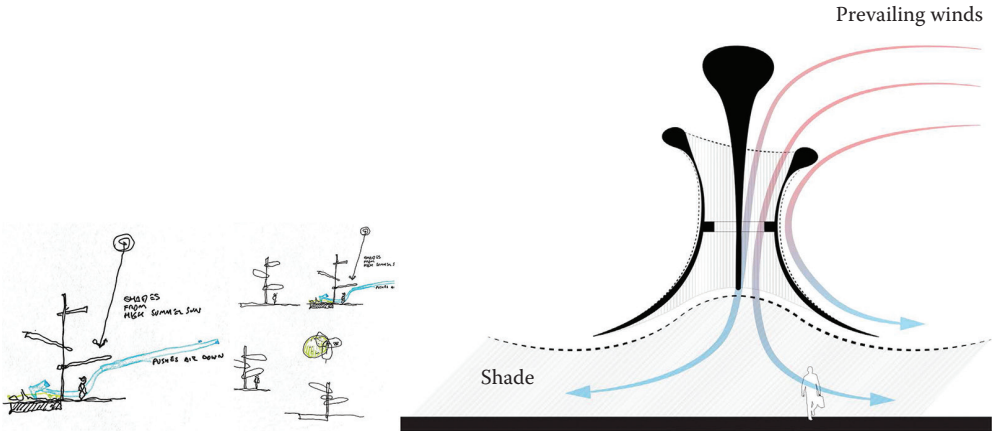


FIGURE 11.58 Conceptual solution that provides shade will increasing wind. (Courtesy of CallisonRTKL.)

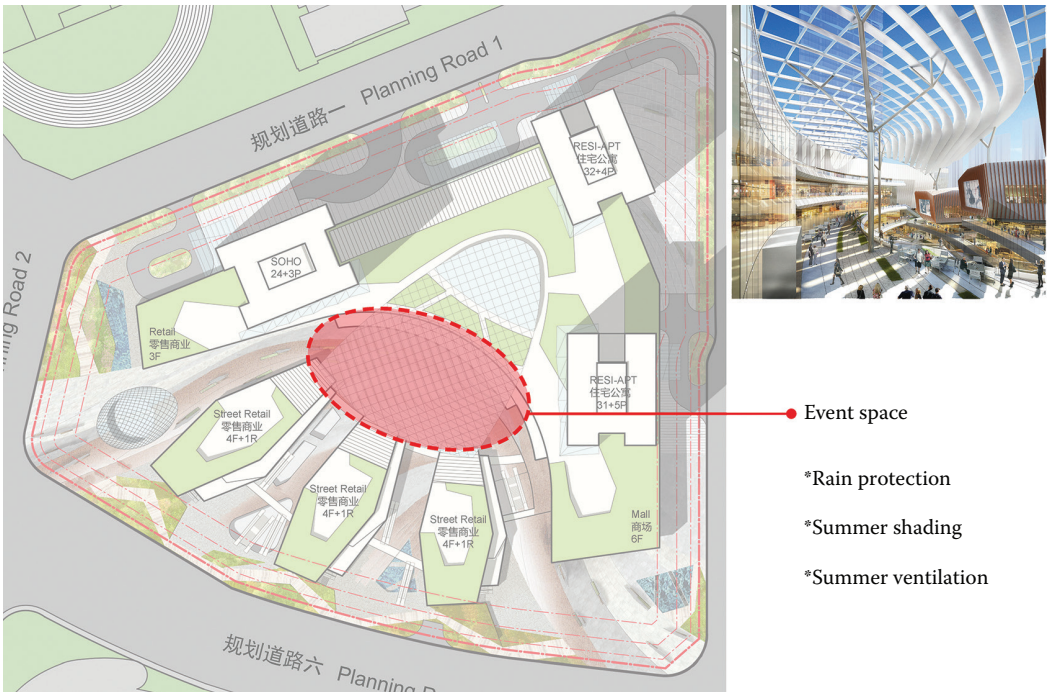


FIGURE 11.59 Location of event space. (Courtesy of CallisonRTKL.)

Figures 11.59 through 11.67 show another example for an outdoor event space in Guiyang China. The goal was to provide continuous outdoor comfort so that the space could be used year round. Figure 11.59 shows the site while Figure 11.60 shows the climate with key dates. Figure 11.61 and 11.62 show the key goals and solar dates and paths. Shade had to be provided during the summer with some solar penetration in the winter while providing protection from the rain and openings for air movement especially during the summer. Several key angles were determined and geometric relationships between them were proposed to achieve required shading or solar

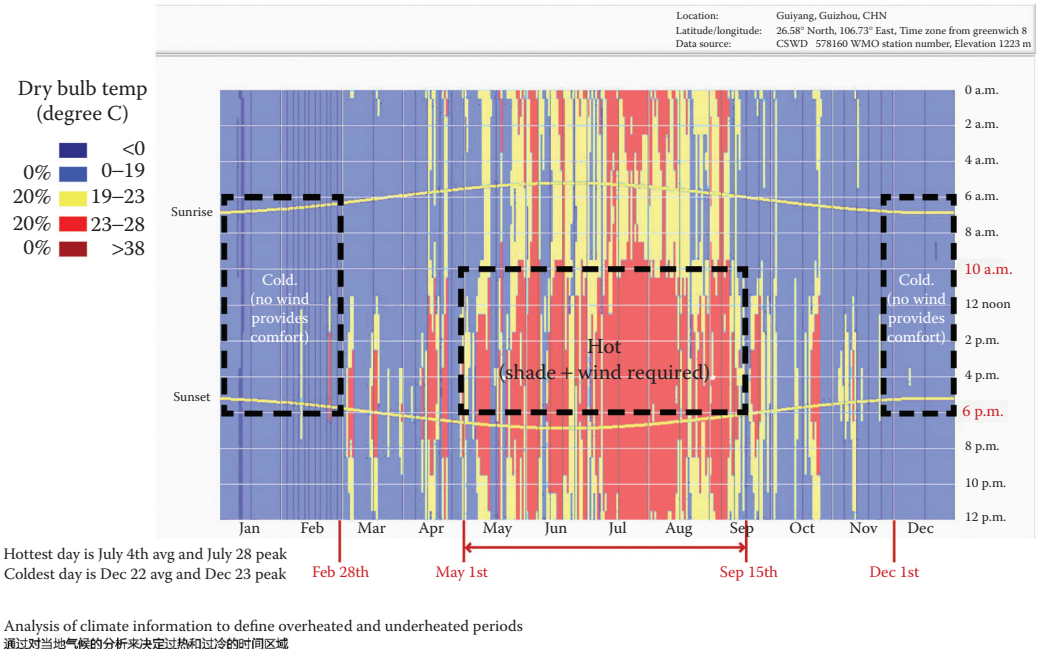


FIGURE 11.60 Timetable plot with temperature and design strategies. (Courtesy of CallisonRTKL.)

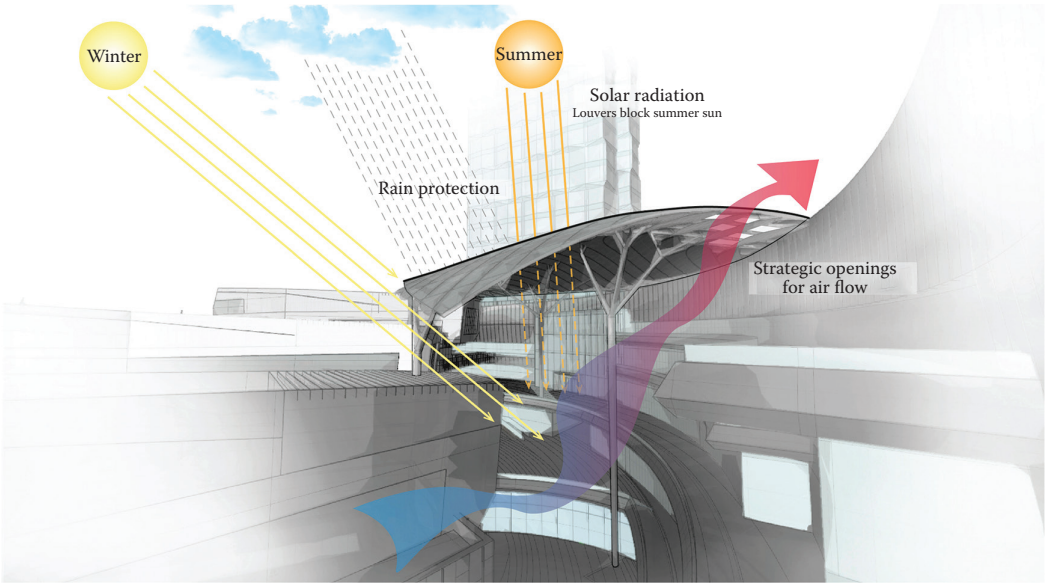


FIGURE 11.61 Canopy design with environmental functions. (Courtesy of CallisonRTKL.)

penetration. The design team generated a grasshopper script for Rhino to develop different types of louvers responding to the geometric relationship rules. Four options were developed and tested for the summer period (Figures 11.64 through 11.66). The option that had the least amount of solar radiation at the ground level was then further developed (Figure 11.67). Figure 11.68 shows the shading effect of the selected canopy during the summer.

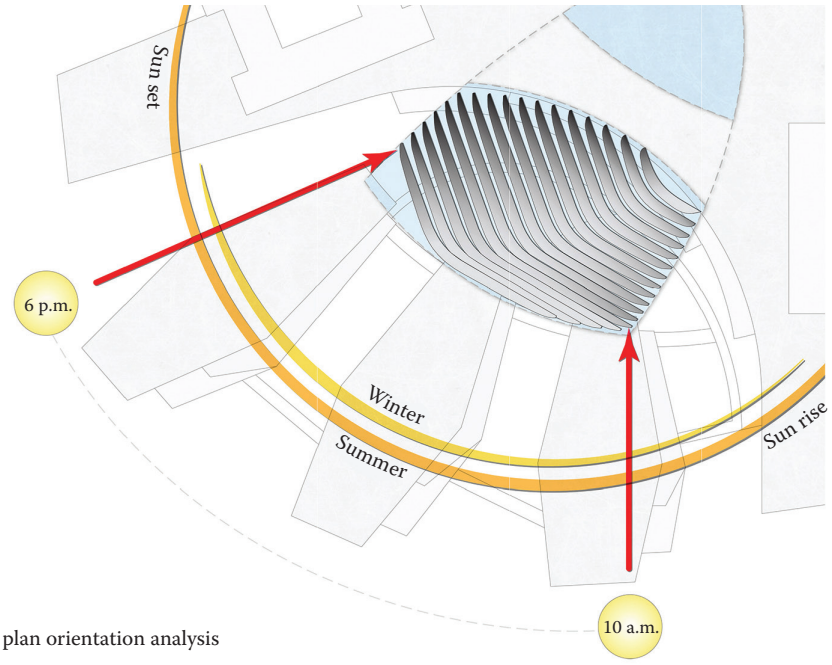


FIGURE 11.62 Canopy solar orientation analysis. (Courtesy of CallisonRTKL.)

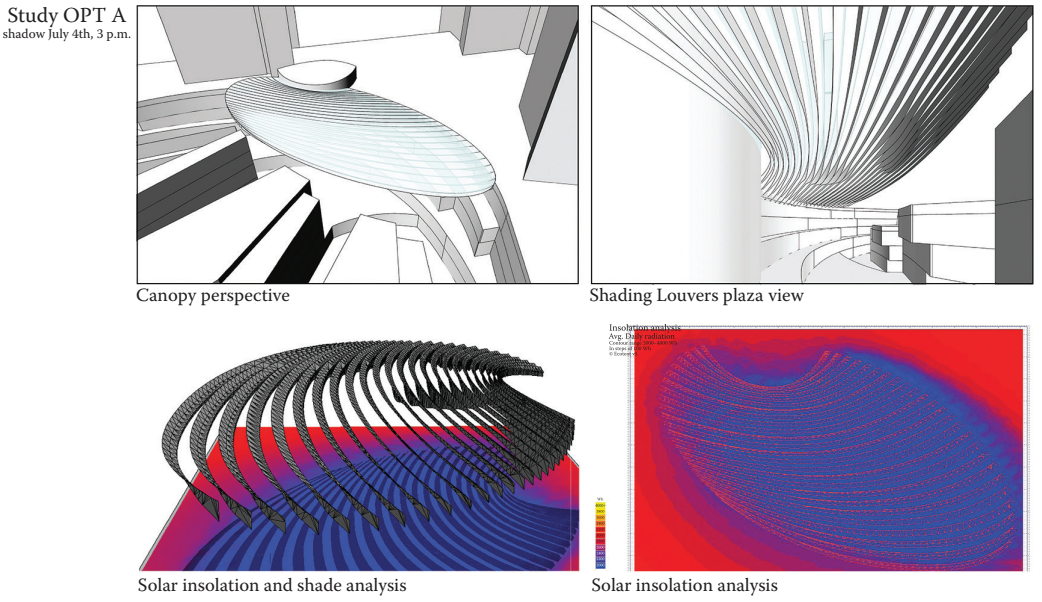


FIGURE 11.63 Option A solar study. (Courtesy of CallisonRTKL.)

Another example of an outdoor comfort design was the Cal State San Bernardino Master Plan Campus proposal in the Palm Desert Campus, in which the sustainability team worked with the CRTKLurban design team and the landscape architects to develop a comfortable outdoor environment under a harsh climate. This new campus is located in California's Climate Zone 15, ASHRAE 90.1 zone 1B, which is very hot dry. This is low desert, characterized by extremely hot and dry

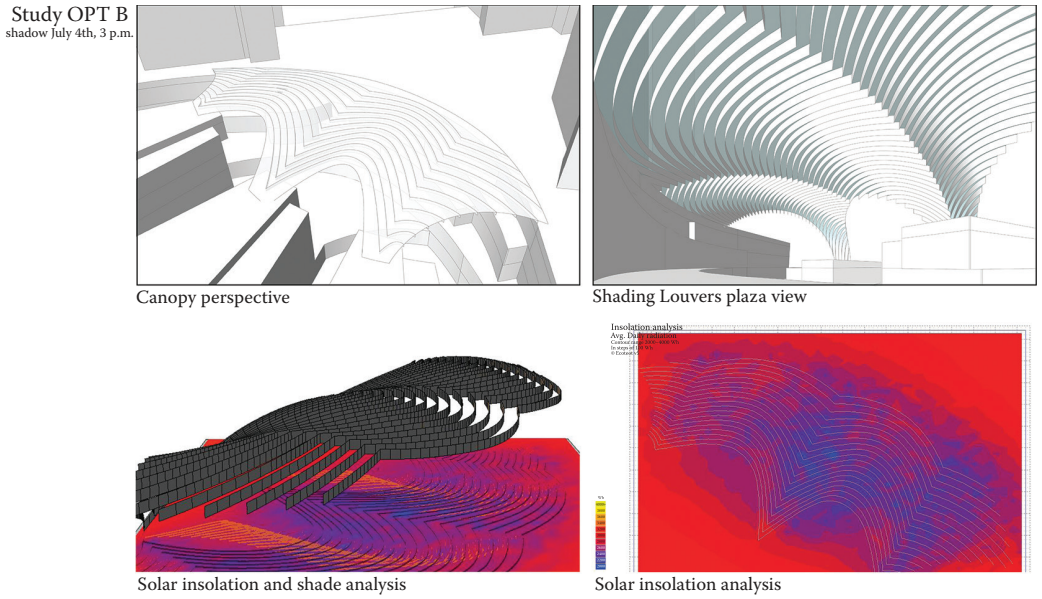


FIGURE 11.64 Option B solar study. (Courtesy of CallisonRTKL.)

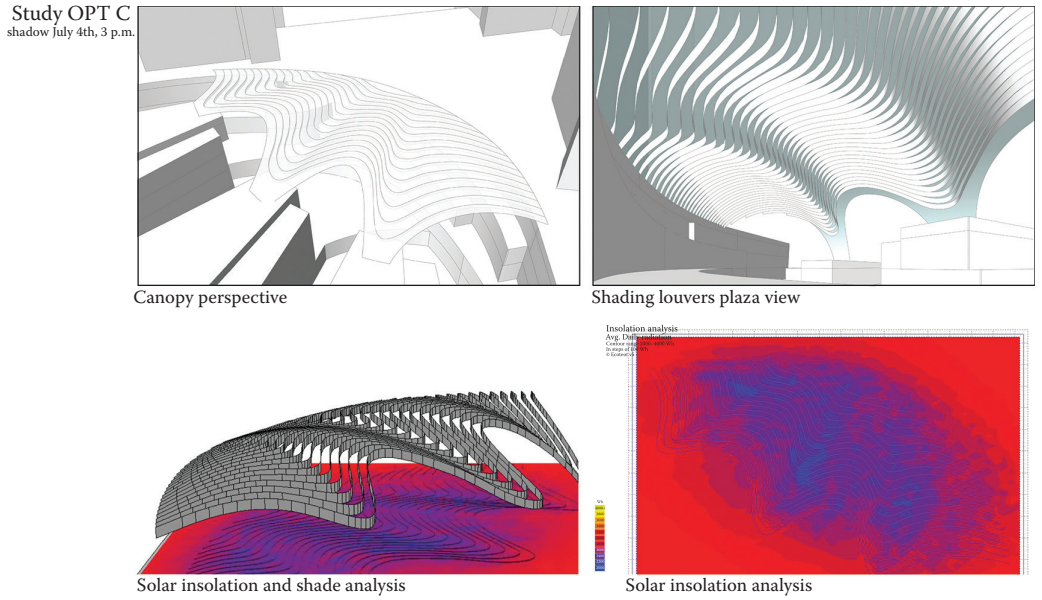


FIGURE 11.65 Option C solar study. (Courtesy of CallisonRTKL.)

summers and moderately cold winters. The average temperature in Climate Zone 15 is much higher than any other zone in California, especially in the summer. The warmest month is July with a max annual temperature of 114.8°F (46°C). The warmest six months are Jul, Aug, Jun, Sep, May, and Oct. The minimum annual temperature is in Jan 39.2°F (4°C). The humidity is below the comfort range much of the year, which results in a large diurnal temperature range and cool nights.

The skies are clear most of the year with an annual sunshine of about 85% and high values of direct solar radiation. The mean daily global radiation is 5,568.7 W/m² (21,765 Btu/h·ft²) and annual

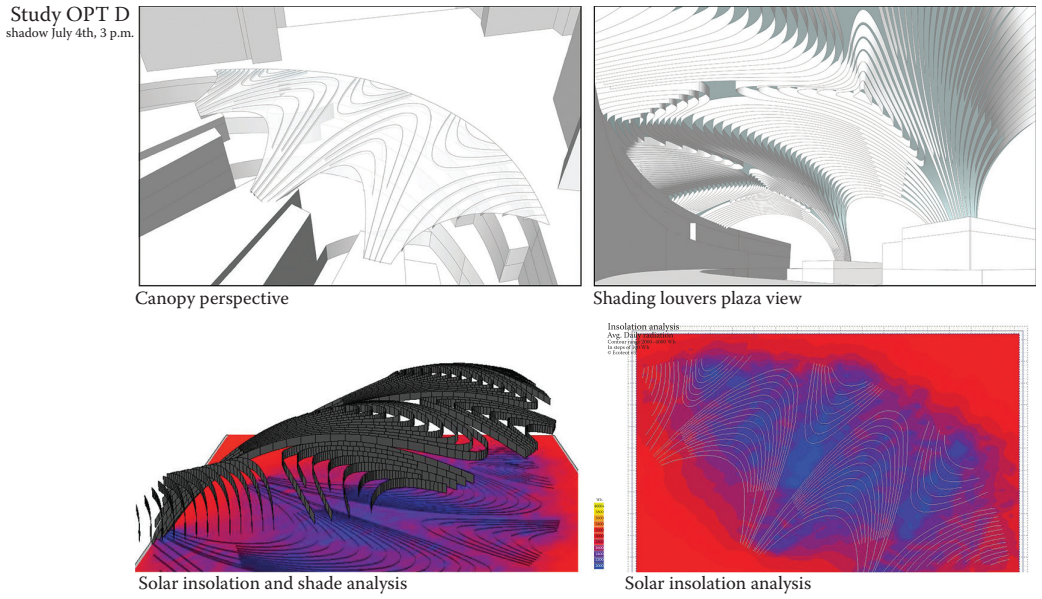


FIGURE 11.66 Option D solar study. (Courtesy of CallisonRTKL.)

FIGURE 11.67 Proposed canopy. (Courtesy of CallisonRTKL.)

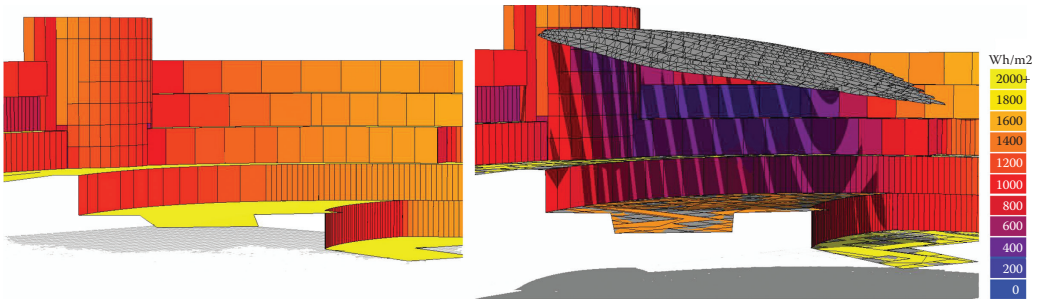


FIGURE 11.68 Solar study in the walls with and without canopy. (Courtesy of CallisonRTKL.)

solar resource 2035.6 kWh/m².yr (645.3 kBtu/ft².yr). Summer storms bring most of the annual precipitation. August is the wettest month, with one inch of rain. The winters are short and mild, and can bring short frosts. While some heating is required during the winter, cooling is the overwhelming concern when designing within Zone 15. Annual prevailing winds are typically from the northwest, while summer prevailing winds are from the northwest and east. Annual mean wind speeds are 11.4 km/hr (10.4 ft/s–3.2 m/s). The climate is hot but there is potential for cooling using the sky at night and evaporative cooling during the daytime when the air is warmest but also driest.

One of the main goals of the outdoor space in this campus is to promote a livable outdoor environment with academic vitality in which students and faculty interact, and a place where teaching and learning continues outside the classroom. Cooling is the overwhelming concern for designing within zone 15. To improve outdoor thermal comfort during this period, certain conditioning strategies can be implemented:

- Minimize solar gains
- Maximize evening/night cooling rate
- Provide evaporative cooling
- Promote air flow
- Building massing to generate shade
- Cool surfaces and landscape

Climate analysis indicates a critical period from early April to the end of October selected for solar studies, during which outdoor temperatures are above the comfort zone between 8 a.m. and 8 p.m., and sometimes all day. Instead of doing studies of the whole campus, three typologies were selected for a more detailed solar and wind study and which could provide insights on the generation of guidelines for the whole campus. Just a small selection of the work is shown here to illustrate the workflow. Figure 11.69 shows an initial sketch of the courtyard scheme by the urban design team. Figures 11.70 and 11.71 show a solar and wind analysis of the same courtyard. Solar analysis shows elevated values of solar radiation in most areas during the summer, especially due to direct solar incidence during the summer afternoon. It is difficult for the wind to enter the courtyard and the lack of exit openings makes it even more difficult for the air to move. Instead the wind moves through the open spaces between the courtyards. Figure 11.72 shows in black required shading due to solar radiation and Figure 11.73 shows the location of the towers based

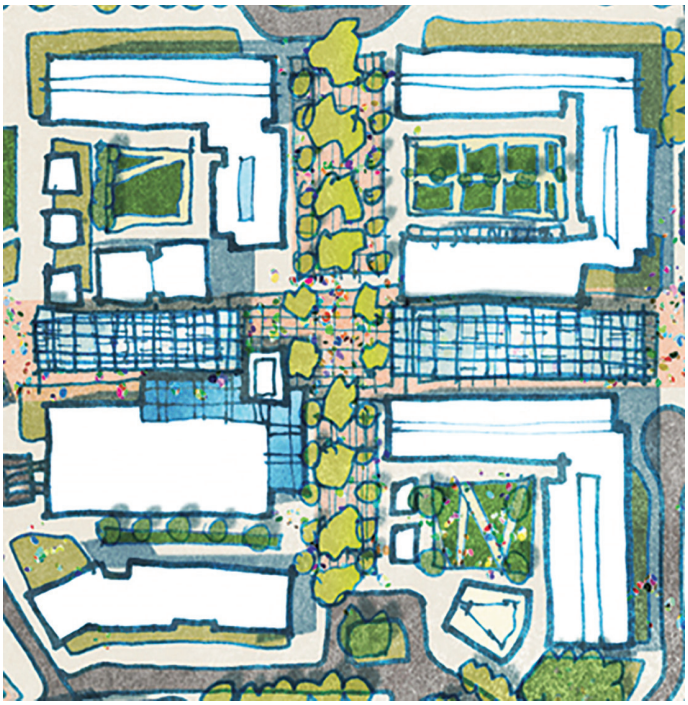


FIGURE 11.69 Initial sketch of the courtyard scheme. (Courtesy of CallisonRTKL.)

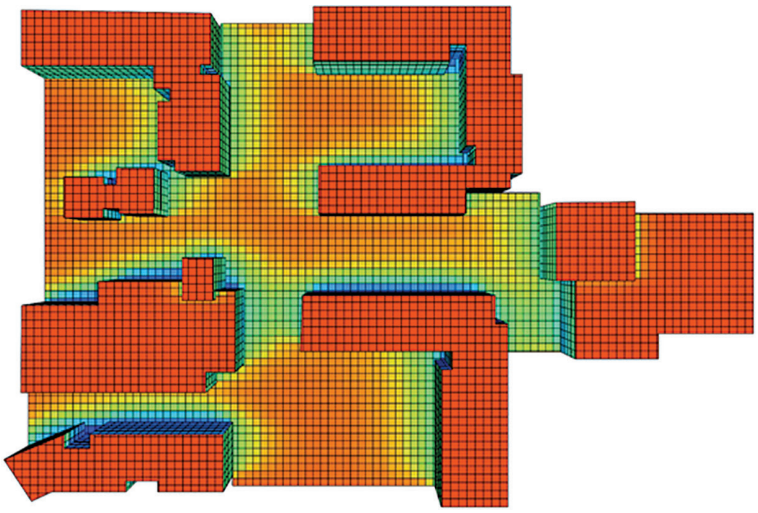


FIGURE 11.70 Solar study of the courtyard scheme. (Courtesy of CallisonRTKL.)

on wind speed. More shade is added where there is more incidence of solar radiation according to Figure 11.70 and it is needed most. Wind scoops are proposed in higher wind speed areas and cool towers in lower wind speed areas at the ground level to keep it from spilling and mixing too much. Figure 11.74 shows a concept for the corridor area in which shade is provided in key areas while allowing for air flow and evaporative cooling to increase comfort. Because the outdoor space is

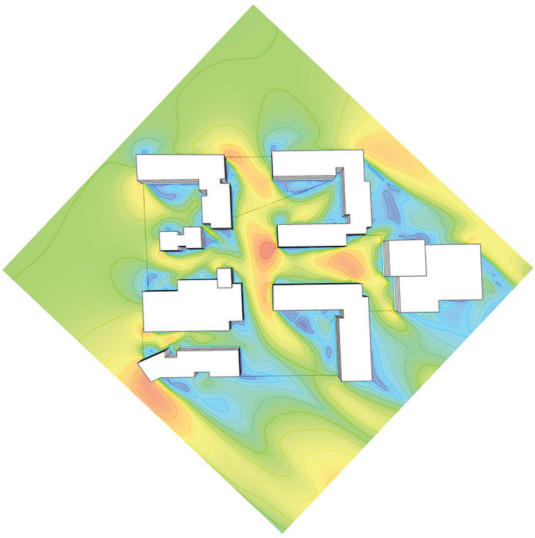


FIGURE 11.71 Wind study of the courtyard scheme. (Courtesy of CallisonRTKL.)

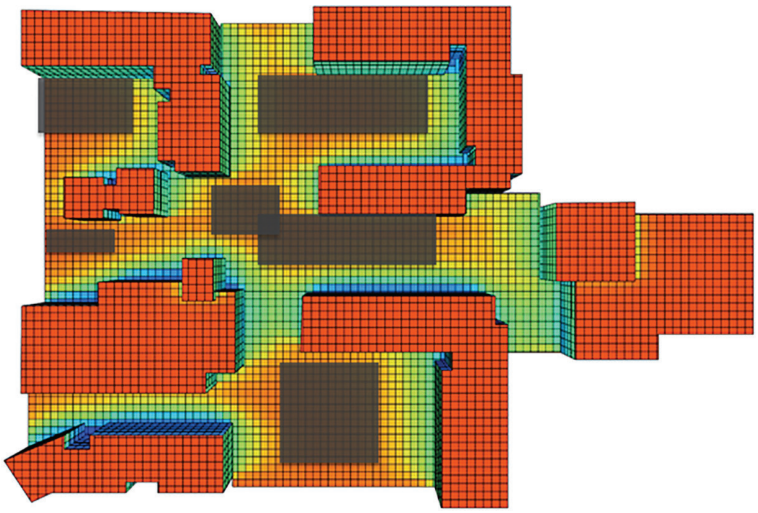


FIGURE 11.72 Required shaded area based on solar study. (Courtesy of CallisonRTKL.)

aligned with the sun's east west path, this option shows elevated values of solar radiation in most outdoor areas (Figure 11.75). The wind enters through openings between the buildings and in the case of the larger south opening to the west expands as it exits the corridor. Toward the east it enters at the north and then exits almost directly toward the south (Figure 11.76).

In this master plan, the three main strategies to make the outdoor more comfortable during overheated periods and which are integrated in the landscape architecture proposal are (a) minimize heat gains, (b) maximize heat losses, and (c) promote evaporative cooling.

Minimize solar gains. Solar gains can be reduced by increasing shade provided by trees. Increasing tree and vegetation cover lowers surface and air temperatures by providing shade and cooling through evapotranspiration. Trees and vegetation can also reduce storm water runoff and protect against erosion. Growing a vegetative layer of native plants on a rooftop reduces temperatures of the roof surface and the surrounding air.

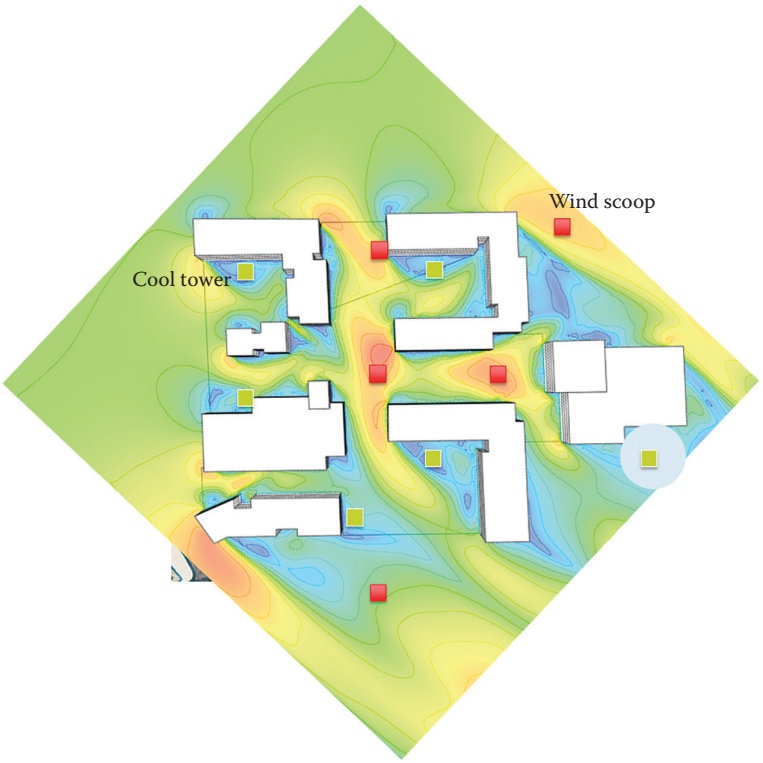


FIGURE 11.73 Options for location of towers based on wind speed. (Courtesy of CallisonRTKL.)

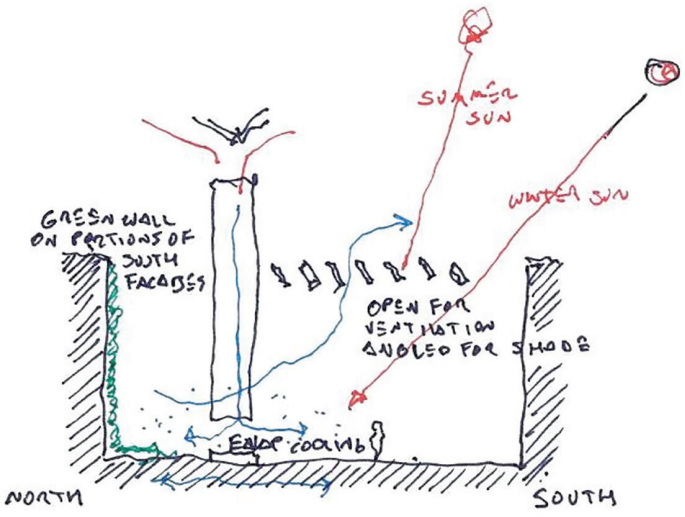


FIGURE 11.74 Sustainable design concept. (Courtesy of CallisonRTKL.)

Installing a cool roof that significantly reflects sunlight and radiates heat away from a building reduces roof temperatures, increases the comfort of occupants, and reduces consumption. Cool pavements on sidewalks, parking lots, and streets that remain cooler than conventional pavements by reflecting more solar energy not only cool the pavement surface, they also cool surrounding air. Canopies and building massing also provide shade.

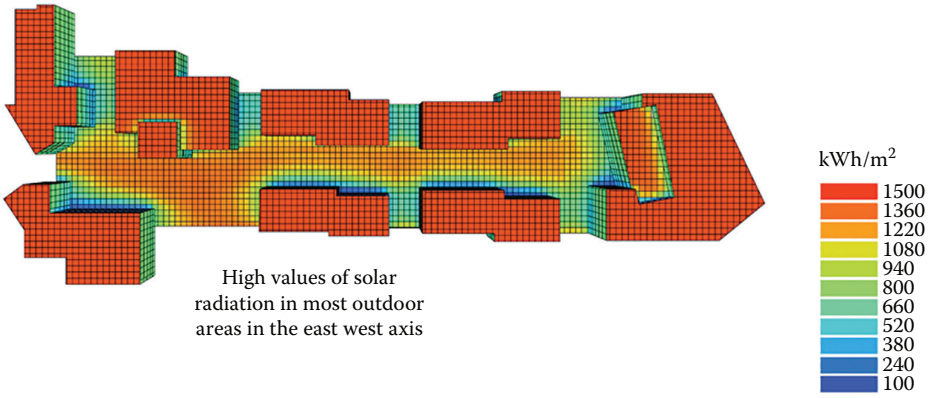


FIGURE 11.75 Solar study with east west axis orientation. (Courtesy of CallisonRTKL.)

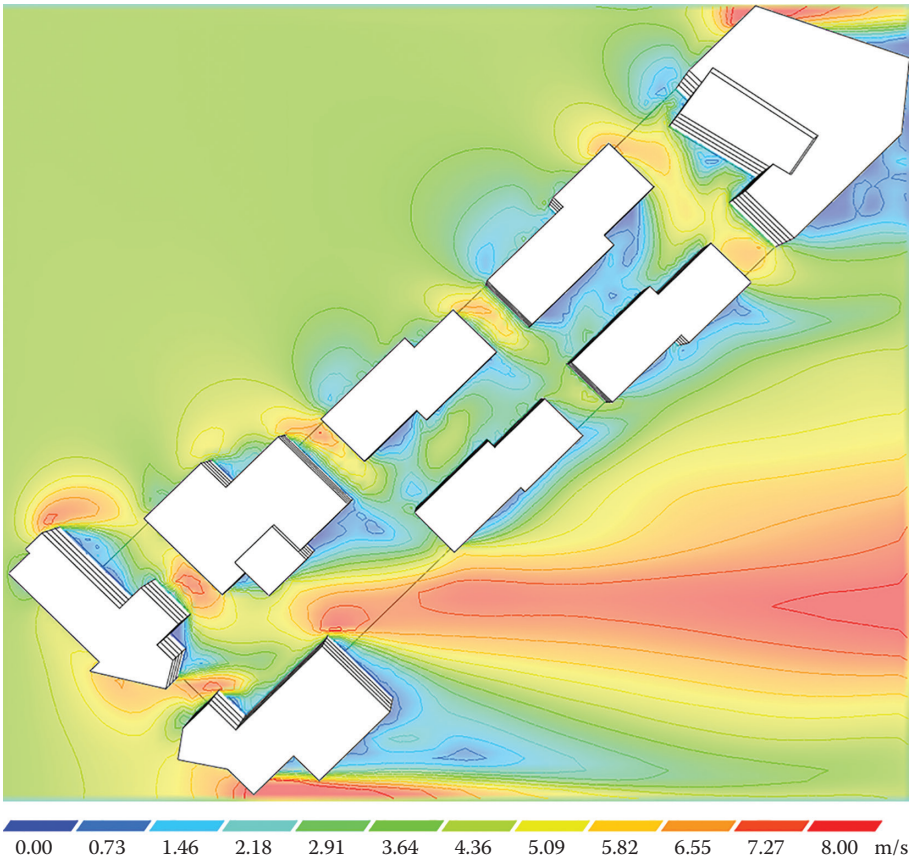


FIGURE 11.76 Wind study with east west orientation. (Courtesy of CallisonRTKL.)

Maximize summer evening/night cooling rate. Because of the clear desert night skies, it is possible to use the sky as a heat sink for the energy that was absorbed during the daytime. This is possible by exposing surfaces such as roofs to the night sky. Pavements and most construction surfaces lose absorbed heat to clear and cooler night skies. Operable shade structures or systems that provide some view of the sky allow the ground below to cool to the sky.

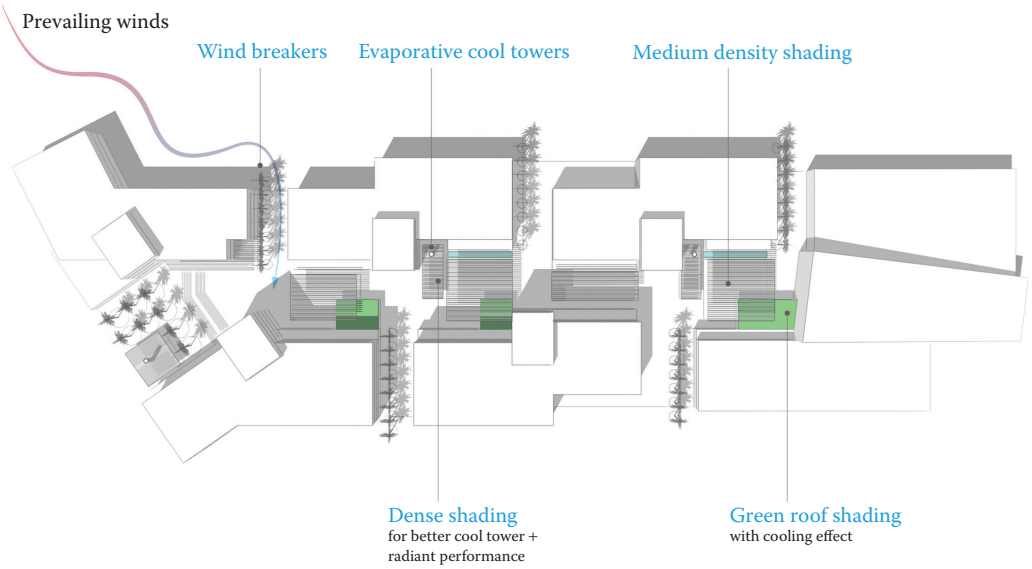


FIGURE 11.77 Network of outdoor strategies for comfort. (Courtesy of CallisonRTKL.)

Evaporative cooling can reduce outdoor air temperature, especially during summer afternoons when the Wet Bulb Temperature Depression is highest. Evaporative cooling can be implemented in many forms, such as fountains, cool towers, or misters. For outdoor use, an enclosure that reduces cool air "leakage" combined with shade is recommended to improve its performance. Evaporative cooling can also be combined with radiant cooling systems. Evaporative cooling systems can be located close to buildings and upwind to cool incoming wind. If structural elements such as towers are used, they can also be used for wayfinding, lighting and to help provide campus identity.

Our team integrated several of these strategies in a proposal to improve outdoor thermal comfort. These strategies include shading, trees, wind breakers, evaporative cool towers, and green surfaces in walls, floors and roofs. Shading can be implemented in different densities depending on the need. This network of strategies is organized so that they provide cooler areas in multiple locations along this path (Figure 11.77). The location and the position of the towers are also based on expected requirements and potential for effectiveness. Additional cooling strategies could be implemented such as radiant systems cooled with the green roofs which then connect to cool benches combined with shade (Figure 11.78).

11.5.3.1 Implementation of Building Simulation in Carbon-Neutral Design Strategies

All of the workflows and strategies described in this chapter are examples of workflows that reduce energy consumption and carbon emission in buildings. If these were implemented in more projects, our impact in the environment would increase. When the author headed HMC Architect's Archlab team, these strategies were implemented in some projects. An example is a school building ideas competition for the Los Angeles Unified School District (LAUSD). The goal in this project was to design a flexible classroom building with a reduced carbon footprint. Different strategies were implemented, which are shown in Figure 11.79. Figures 11.80 through 11.82, produced by E. Carbonnier, indicate where these strategies can be implemented in the building, while Figure 11.83 compares the emissions in each of the four areas with those of an equivalent size school building. Even though this project was not selected by the LAUSD, it provides insight into potential strategies to achieve low carbon school buildings using energy simulation tools to validate ideas.

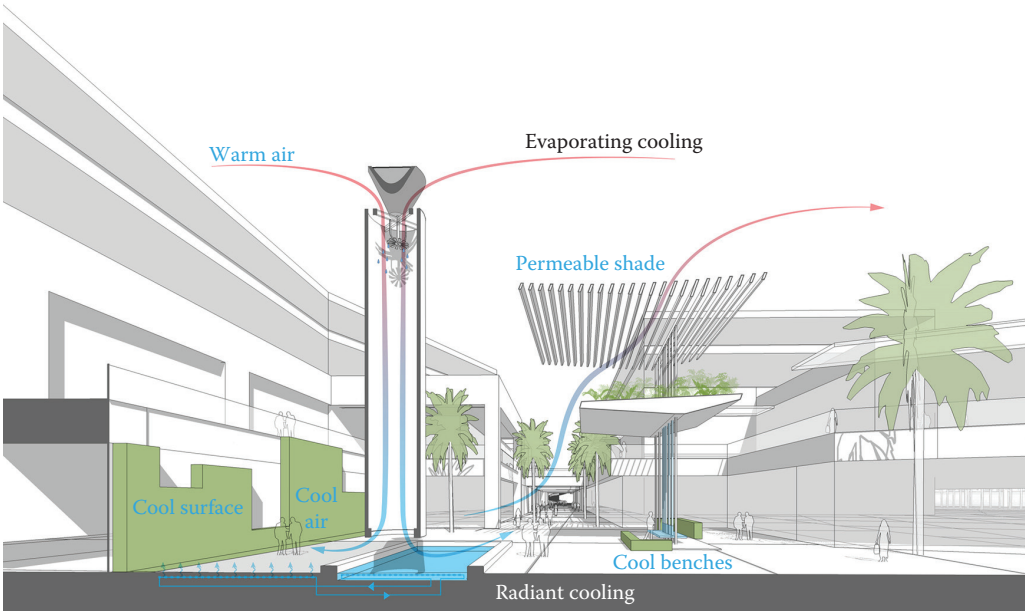


FIGURE 11.78 Outdoor cooling strategies. (Courtesy of CallisonRTKL.)

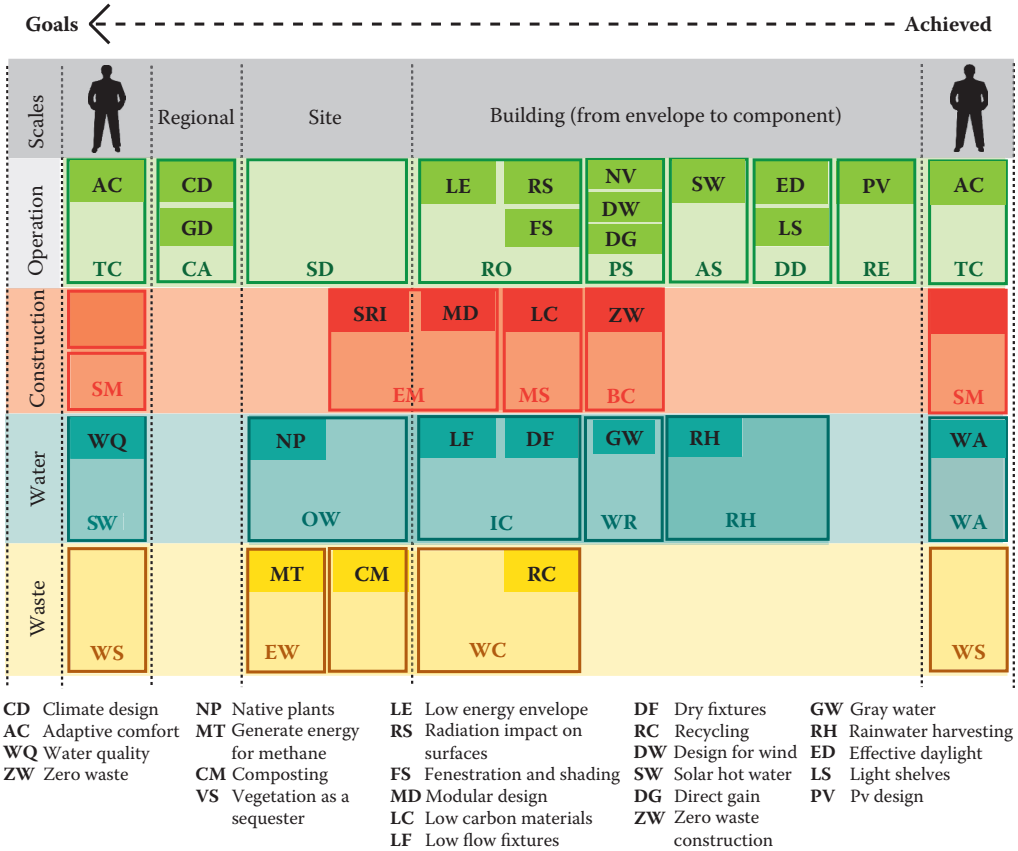


FIGURE 11.79 Carbon-neutral design strategies implemented for the flex school building.

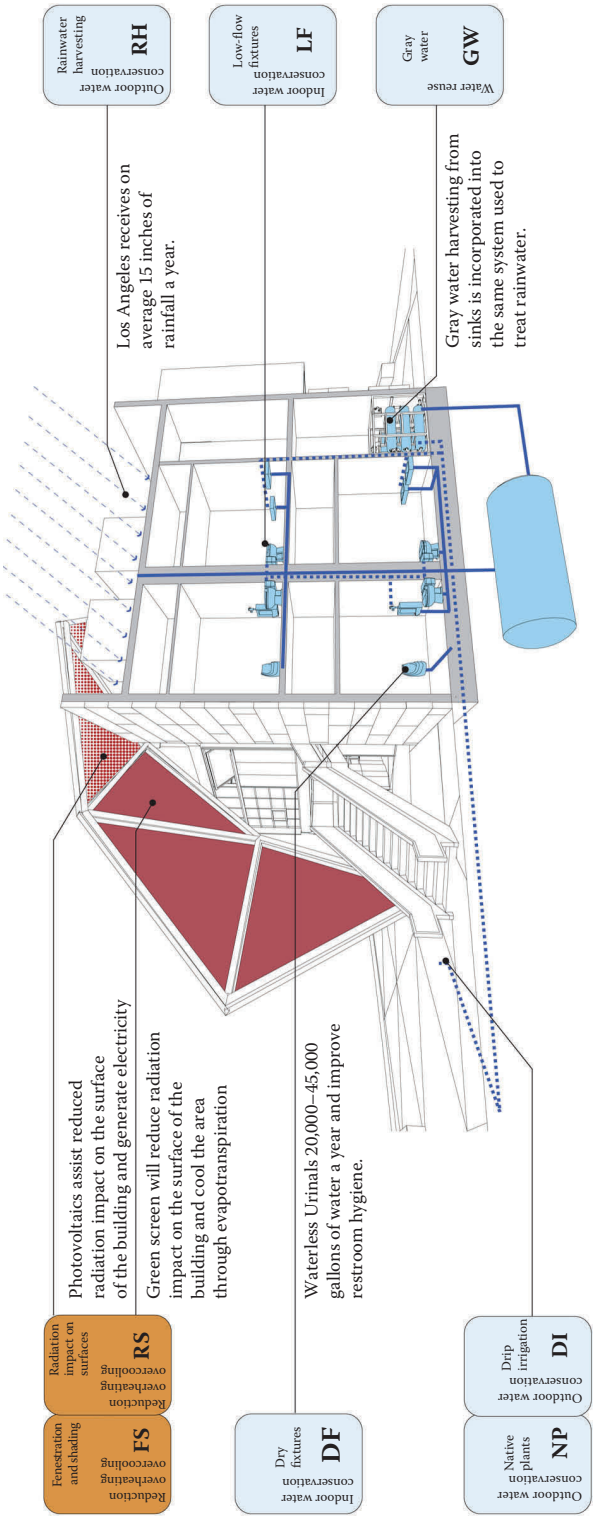


FIGURE 11.80 Water and energy strategies for flex school building. (Courtesy of HMC Archlab.)

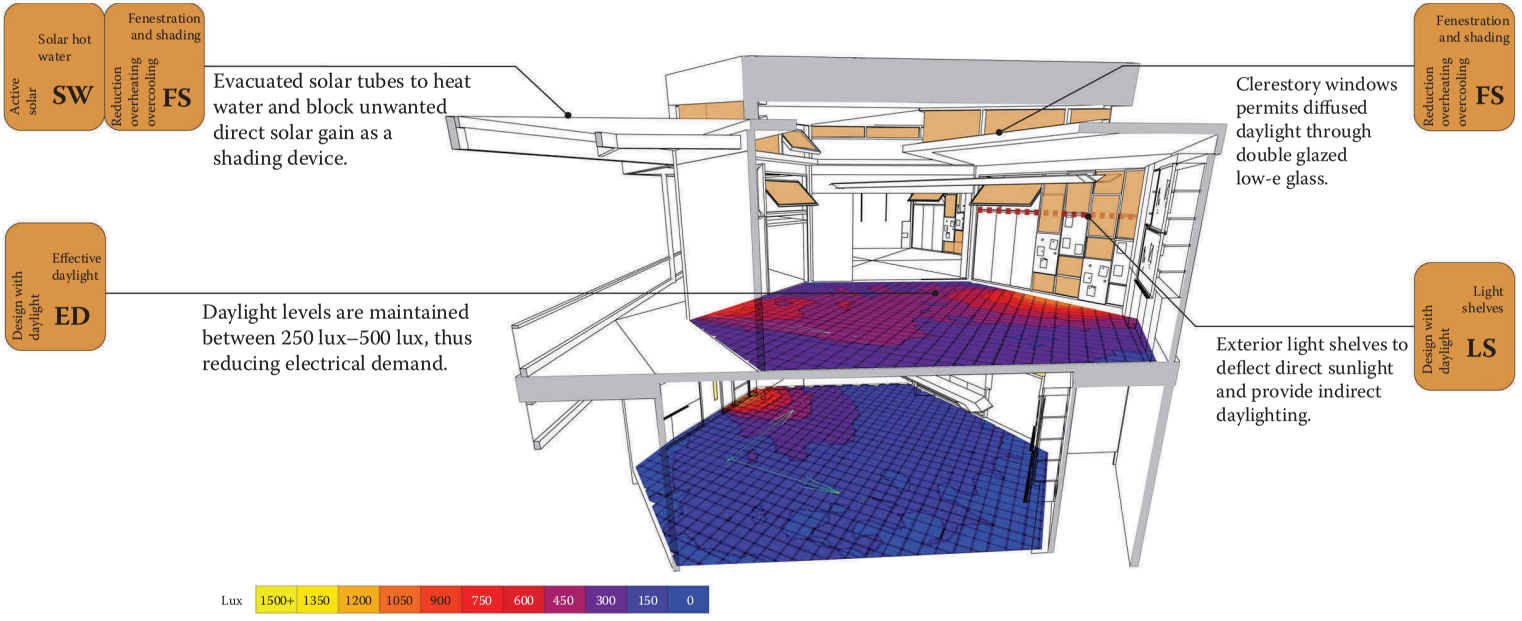


FIGURE 11.81 Water and energy strategies for flex school building. (Courtesy of HMC Archlab.)

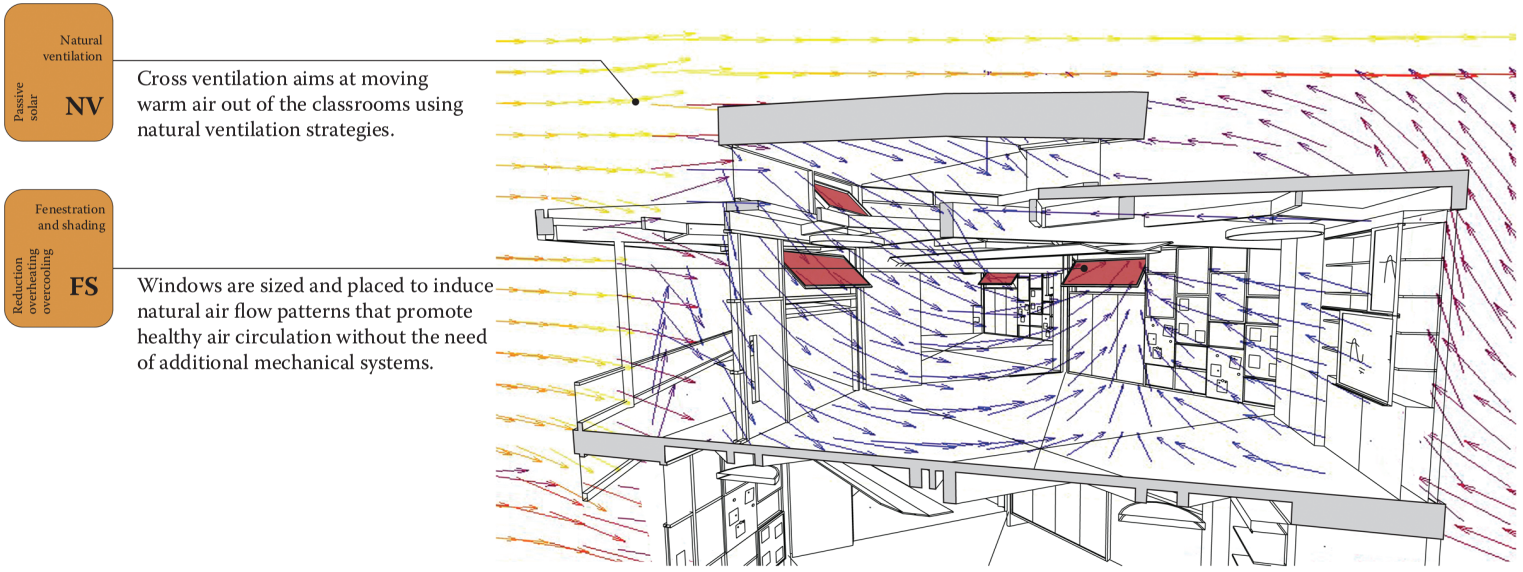


FIGURE 11.82 Energy strategies for flex school building. (Courtesy of HMC Archlab.)

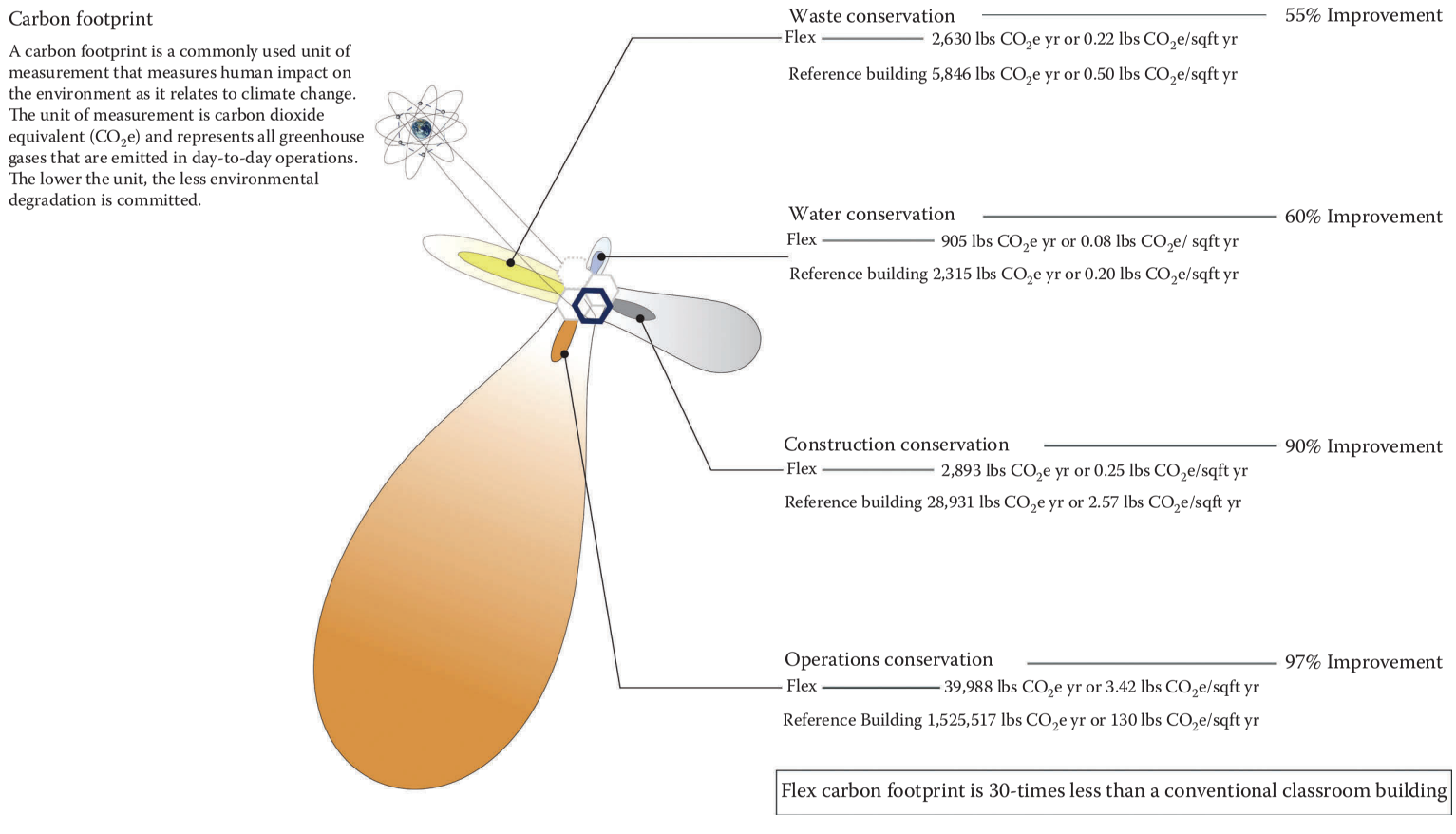


FIGURE 11.83 Comparison of emissions for flex school building. (Courtesy of HMC Archlab.)

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