ENERGY EFFICIENCY DESIGN STRATEGIES FOR BUILDINGS WITH GRID-CONNECTED PHOTOVOLTAIC SYSTEMS

by

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DEDICATION

To my family

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LIST OF ABBREVIATIONS, DEFINITIONS AND ACRONYMS

A	Ampere (electric current)
AC	Alternative Current
AFUE	Annual Fuel Utilization Efficiency
ACH	Air Changes per Hour
ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc.
ASHRAE 90.1	ANSI/ASHRAE/IESNA 90.1 Energy Standard for Buildings except Low-Rise Residential Buildings
ASHRAE 90.2	Energy-Efficient Design of Low-Rise Residential Buildings
ASTM	American Society for Testing and Materials
BA	Building America
BECP	Building Energy Code Program
BMS	Building Management System
Btu	British thermal unit
°C	Degree Celsius
C-factor	Thermal conductance of construction assemblies from surface to surface. C-factor does not include adjacent ground or air films, expressed in W/mK (Btu/h.ft^2/°F)
CBECS	Commercial Building Energy Consumption Survey
CDD	Cooling Degree-Day
CDD10	Cooling Degree-Day base 10°C
CFD	Computational Fluid Dynamics
cfm	Cubic feet per minute

ci	Continuous insulation
COP	Coefficient of Performance
DC	Direct Current
DHW	Domestic Hot Water
DNI	Direct Normal Irradiance
DOE	Department of Energy
DX	Direct Expansion
EER	Energy Efficiency Ratio
EF	Energy Factor
EIA	Energy Information Administration
EPA	Environmental Protection Agency
EPAct	The federal Energy Policy Act
EPCA	Energy Policy and Conservation
E_{sc}	Solar constant
eV	Electron Volt
F	Fahrenheit
F-factor	The parameter heat loss factor for slab-on-grade floor from indoor air, construction assemblies to soil, expressed in W/m^2K (Btu/h.ft.°F)
ft	Foot
GHI	Global Horizontal Irradiance
h	Hour
HDD	Heating Degree-Day
HDD18	Heating Degree-Day base 18°C
HERS	Home Energy Rating System
hp	Horsepower
HP	Heat Pump
HSPF	Heating Seasonal Power Factor

HVAC	Heating, Ventilating, and Air Conditioning
ICC	International Code Council
IECC	International Energy Conservation Code
IEER	Integrated Energy Efficiency Ratio
IESNA	Illumination Engineering Society of North America
in.	Inch
in. WC	Inches water column
K	Kelvin
kg	Kilogram
kW	Kilowatt
kWh	Kilowatt-hour
LBNL	Lawrence Berkeley National Laboratory
LDC	Load Duration Curve
LEED	Leadership in Energy and Environmental Design
LPD	Lighting Power Density
m	Meter
mc-Si	Multicrystalline silicon
MECS	Manufacturing Energy Consumption Survey
mono-Si	Monocrystalline silicon
NAECA	National Appliance Energy Conservation Act
NRCC	Northeast Regional Climate Center
NREL	National Renewable Energy Laboratory
NSRDB	National Solar Radiation Database
poly-Si	Polycrystalline silicon
PV	Photovoltaic
R	R-value (thermal resistance)
RECS	Residential Energy Consumption Survey

RESNET	Residential Energy Services Network
RPS	Renewable Portfolio Standard
SC	Shading Coefficient
SEDS	State Energy Data System
SEER	Seasonal Energy Efficiency Ratio
SHGC	Solar Heat Gain Coefficient
TMY	Typical Meteorological Year
TMY2	Typical Meteorological Year, Version 2
TMY3	Typical Meteorological Year, Version 3
TOU	Time of Use
TRNSYS	TRaNsient SYstem Simulation Program
U-factor	Thermal transmittance
USGBC	U.S. Green Building Council
V	Volt (a unit of electrical force)
VAV	Variable Air Volume
VRF	Variable Refrigerant Flow
VT	Visible Transmission
W	Watt
WWR	Window to Wall Ratio

ABSTRACT

The building sector in the United States represents more than 40% of the nation's energy consumption. Energy efficiency design strategies and renewable energy are keys to reduce building energy demand. Grid-connected photovoltaic (PV) systems installed on buildings have been the fastest growing market in the PV industry. This growth poses challenges for buildings qualified to serve in this market sector.

Electricity produced from solar energy is intermittent. Matching building electricity demand with PV electricity output can increase PV system efficiency. Through experimental methods and case studies, computer simulations were used to investigate the priorities of energy efficiency design strategies that decreased electricity demand while producing load profiles that match the unique output profiles from PV. Three building types (residential, commercial, and industrial) of varying sizes and use patterns located in 16 climate zones were modeled according to ASHRAE (American Society of Heating, Refrigerating and Air-conditioning Engineers) 90.1 requirements. Buildings were analyzed individually and as a group.

Complying with ASHRAE energy standards can reduce annual electricity consumption at least 13%. With energy efficiency design strategies, the reduction could reach up to 65%, making it possible for PV systems to match reduced usage demands in residential and industrial buildings. The peak electricity demand reduction could be up to 71% with integration of strategies and PV. Reducing lighting power density was the best single strategy with high overall performances. Combined strategies, such as ZEB (Zero Energy Building), are also recommended. Electricity consumption reductions are the sum of the reductions from strategies and PV electricity output. However, peak electricity

reductions were less than their sum because they reduced peak at different times. The potential of grid stress reduction is significant. Investment incentives from government and electricity utility companies are necessary. The PV system sizes on net metering interconnection should not be limited by legislation that currently exists in some states.

Data from this study provides insight into the impact of applying energy efficiency design strategies in buildings with grid-connected PV systems. With the current transition from traditional electric grids to future smart grids, this information plus large databases describing various building conditions will allow possible investigations needed by governments or electric utility companies in large scale communities for implementing various measures and policies.

CHAPTER 1
INTRODUCTION

The building sector is the largest energy consumer in the United States. Reducing buildings' fossil fuel-based energy demand can be achieved by the use of energy efficiency design strategies and on-site renewable energy sources such as photovoltaic (PV) systems. These two components are often viewed and implemented as separated processes. However, some energy efficiency design strategies could work with a grid-connected PV system, and together they could give more benefits than in the typical separate implementation. This study investigated these relationships in residential, commercial, and industrial buildings of various sizes and use patterns located in different weather zones. These models and simulations resulted in a large database of various building energy use conditions, allowing the analysis of buildings as a community or cluster in deployment of energy efficiency design strategies and grid-connected PV systems.

1.1 Background

In 2009, the building sector consumed 41% of total energy consumption, while transportation and industry accounted for 28% and 31% respectively (Energy Information Administration [EIA], 2011b). Building operation alone accounts for 75% of electricity used in the United States, making it not only the largest electricity consumer but the major source of pollution and greenhouse gas emissions. Large centralized fossil-fueled power plants generate most traditional electricity, followed by nuclear power plants. From these plants, electricity is transported through transmission grids to buildings, but electricity produced this way is inefficient. More than 50% of input energy is lost during electrical generation, transmission, and distribution. Moreover, the main fuel sources for these power plants – mostly coal, natural gas, and uranium – are non-renewable. With the current rates of electricity consumption, these resources will not be able to meet the long-term demand. There are also other environmental problems associated with these types of power plants such as air pollution, water pollution, radioactive pollution, and greenhouse gases.

The architectural design community has realized that future buildings must incorporate sustainable design practices to reduce impact to the environment, while maintaining the occupants' wellness and productivity. Reducing building energy use is the main emphasis in this process. Designs following energy efficiency codes and standards can reduce energy use by 30% over conventional consumption. However, to reach a 50% or more reduction, integration with renewable energy applications is necessary (USGBC Research Committee, 2007). Renewable energy use in the building sector is accelerated by a federal tax credit giving a tax deduction to projects installing renewable energy technologies. Renewable Portfolio Standard (RPS) regulations are another mechanism now implemented in more than half of the states in the U.S. (DSIRE, 2012), setting targets for increasing energy production from renewable energy sources. The RPS places a requirement for electric utility companies to produce or buy a specified fraction of their electricity from renewable energy sources. These renewable energy systems in buildings are considered electricity generators that can also sell their certified electricity back to the electric utility companies.

In architectural practice, one of the major movements combining energy efficiency design practices with the use of renewable energy is the Architecture 2030 challenge asking architects to implement its target in their designs. Architecture 2030 is a nonprofit advocacy group established in 2002 to focus on achieving a rapid reduction in greenhouse gas emissions caused by the building sector (Architecture 2030, 2012). The target of Architecture 2030 is to reduce energy dependence on fossil fuel based power plants. This can be accomplished by implementing energy efficiency design strategies to cut building energy use by half compared with conventional designs, generating at least 30% of energy used in buildings by on-site renewable powers, and purchasing up to 20% green energy from electric utility companies (Figure 1).

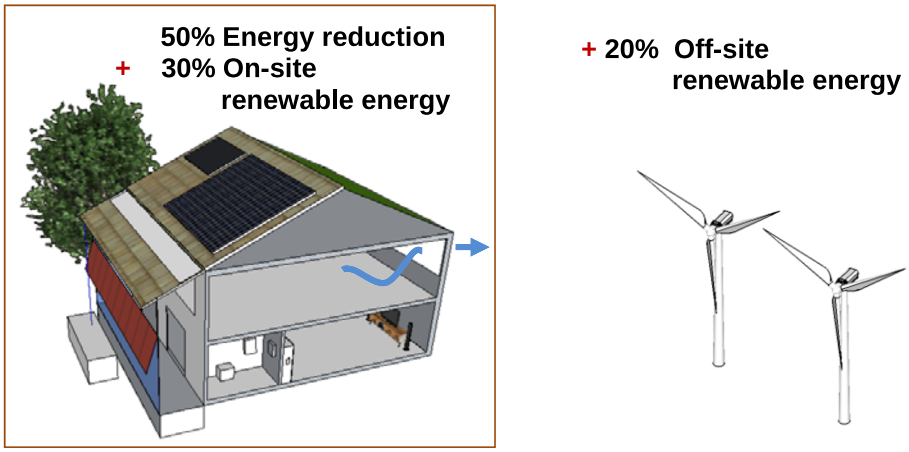


Figure 1. Architect 2030 strategies to reduce energy dependence on fossil fuel (Architecture 2030, 2012).

1.2 Building Energy Efficiency Design Strategies

Energy efficiency buildings use less energy to operate, but still provide the same services and functions that satisfy building occupants in less efficient buildings. Design standards and guidelines for energy efficiency designs are currently well established. The energy crisis in 1970s led the U.S. government to pass the Energy Policy and Conservation Act (EPCA) in 1975 to establish the country's energy resource reserves and promote energy conservation. In the U.S., building energy codes are the local governments' responsibility. In 1992, Congress passed the Energy Policy Act (EPAct) requiring all states to review and consider adopting the national model energy standard. There are currently two codes and standards that are usually adopted by local governments: 1) ANSI/ASHRAE/IESNA 90.1 Energy Standard for Buildings except Low-Rise Residential Buildings (ASHRAE 90.1) developed by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE); and 2) the International Energy Conservation Code® (IECC) developed by the International Code Council (ICC). Both ASHRAE 90.1 and IECC are written in forcible language, making them easily adopted. They have also been developed in open public review forums. More stringent standards and guidelines are available and usually built upon the ASHRAE 90.1 and the IECC. Architects need to design buildings within available budgets that meet all requirements from energy codes, such as building envelope, building systems, and lighting systems. Complying with energy codes also affects the materials selected for the building, for example, the type and performance of glazing, level of insulation, and lighting system that meet code requirements.

The federal Energy Policy Act of 2005 (EPAct 2005) section 1331 gives energy efficiency tax deductions to existing and new building owners up to $18/ m^2 ($1.80/ ft^2) of the building if its energy use is less than 50% of buildings that meet the minimum requirements of the ASHRAE 90.1-2001 standard until the end of 2013. The Leadership in Energy and Environmental Design (LEED) rating systems give credits or points according to a building's compliance level to the ASHRAE 90.1-2007 standard. A building can receive up to 19 points in LEED for New Construction 2009, if the proposed design consumes energy less than 44% in an existing building or 48% in new construction compared with the baseline building in accordance with ASHRAE 90.1-2007.

Energy efficiency design strategies can be divided into three main categories: architectural components, building systems, and building management. Examples of strategies are:

- Architectural components
    - Increase insulation level
    - Use high performance glazing
    - Add external shading devices above glazing façade
    - Passive solar strategies such as using thermal mass
    - Daylighting
- Building systems
    - High efficiency air conditioning system

    - High efficiency heating system
    - Switch from gas-based systems to electricity-based systems
- Building management
    - Thermostat setpoint temperature
    - Setback temperature

1.3 Grid-Connected PV Systems as Renewable Energy Sources

Energy source availability is the first criterion in selecting renewable energy power systems to implement in a building. The National Renewable Energy Laboratory (NREL) provides U.S. renewable energy resource potential maps on its website. When there are multiple resources available at the same location, building simulation can be used to identify the potential energy sources by comparing generating capability, lifetimes, and feasibility. Other factors such as land area needed and noise pollution from plants should also be considered. Among renewable energy sources available for buildings, solar electric systems or PV systems are a good option for the following reasons:

- The systems are easy to install on building rooftops without the need for land areas. Modulation characteristics make the system size and shape flexible.
- Solar energy has the highest capacity compared with other energy sources. U.S. energy demand will increase 25% by the year 2035 (EIA, 2010b). The country is facing a challenge to provide enough energy for the increasing demand. Solar energy is a perfect sustainable energy resource supply for the future because it is free, unlimited, and available everywhere.
- When the system is in operation, it generates no noise and no pollution, and requires little maintenance.
- The life span of PV modules is long. Some systems installed 30 years ago are still functioning today. The electricity output warranty is 20 to 25 years, depending upon the manufacturer.

- Life cycle assessments of PV products from various sources show that system lifetime CO_2 emission per kWh is 5 to 40 times less than traditionally produced electricity (Varun, Bhat, & Prakash, 2009). During its lifetime, PV modules produce around 15 times the energy used to manufacture the modules, making the energy payback period approximately 2 years.
- The photovoltaic system is a matured technology that has been available for decades. Today, with incentive programs from governments, along with increasing PV production and decreasing cost of PV systems, the availability of net metering that allows the interconnection between PV systems and the electric grid and strong consumer demand, urban grid-connected systems have become the most active sector of the PV market. In grid-connected PV systems, the electric grid acts as virtual energy storage. The excess PV production during the day can be sent to an electric utility grid, and at night when there is no sun, electricity from the electric utility grid can be used to meet the building demand. A typical grid-connected PV system diagram is shown in Figure 2.

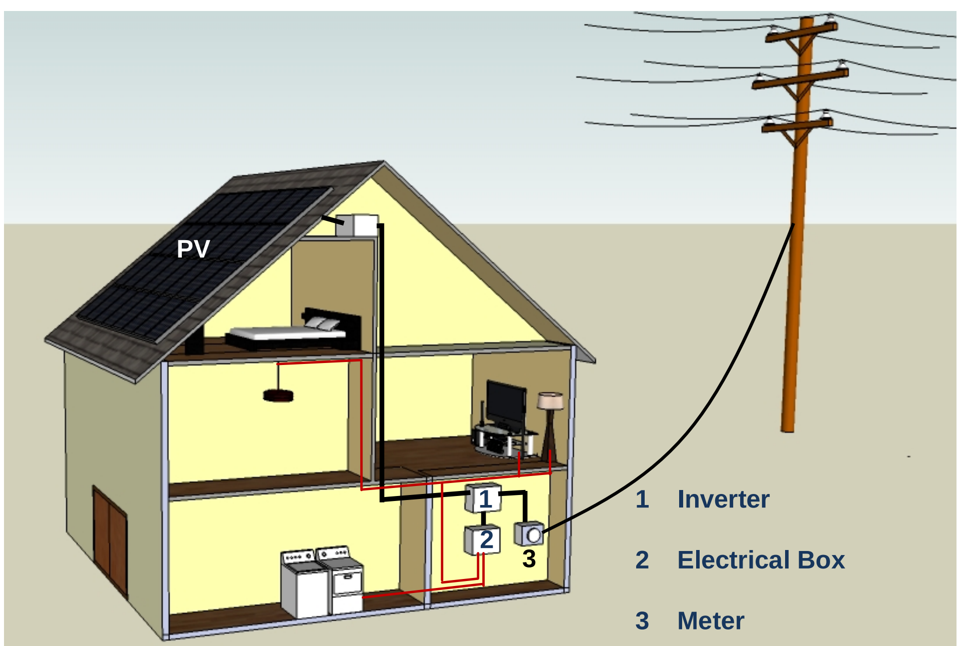


Figure 2. A typical diagram of grid-connected photovoltaic systems.

Grid-connected PV implementations in urban contexts are a fairly recent phenomenon that has developed in the last 10 years. Since 2000, grid-connected installations grew from fewer than 50 MW capacities to more than 2,150 MW capacities (Sherwood, 2011). With grid-connected PV systems, building owners become less dependent on the electric grid. In the event of blackout or disaster, the system with energy storage can still provide electricity as long as solar energy is available, thus improving energy security. PV systems with energy storage also help improve electricity quality by maintaining the continuity when blackout or voltage dips occur. Contrasting with its high investment, there is no cost for the fuel, resulting in electricity price security.

Peak electricity demand, especially in summer, normally happens when solar radiation is strong. This leads to heavy use of air conditioning systems. However, solar energy is also the primary fuel for PV systems. In buildings where electricity loads have a strong influence from their envelopes, building load profiles have a high correlation to the electricity output profiles from PV systems. Therefore, PV systems have a high potential to help reduce grid stress during heavy electricity demand periods in summer (Perez & Collins, 2004; Perez, Letendre, & Herig, 2001). Buildings with grid-connected PV systems will have the ability to reduce their own peak load demand, making them qualified for discounted electricity rates.

PV systems connected to the electric grid can also be used as peak load power plants, in combination with base load power plants such as coal and nuclear power plants, and load-following power plants, such as natural gas power plants. Thus, they can help slow down the need for new fossil fuel power plants. Also, they are normally located on sites that help reduce the need to build or upgrade electric distribution systems. PV systems also introduce a good mix of power plants based on different fuels that improve the reliability of the electric grid system. Overall, interconnection between PV systems and the electric grid allows for more effective utilization of electricity generated from PV systems, creates effective wholesale competition, and creates grid reliability.

Despite the rapid growth in grid-connected PV systems, as well as large scale PV power plants, PV production accounted for only 0.11% of the country's total energy consumption (EIA, 2011b). This represents the huge gap between the undeveloped potential of solar energy and its present use. On the other hand, this implies that the opportunity to implement these systems in the building sector is high. It is also estimated that building floor space will increase approximately 30% in 2035 (EIA, 2011a), indicating opportunities to incorporate PV systems in future renovation and new projects. The main challenges in implementing grid-connected PV systems are solar availability, intermittency, grid support, and high capital cost. Two other challenges subject to psychological issues – aesthetic and social added values – were not considered in this study.

Solar availability. The intensity and duration of solar radiation can vary from location to location. Areas near the equator and areas with clear skies normally receive high levels of solar radiation. Figure 3 shows the annual PV electricity output from a 4 kW DC system placed at 0°, 30° and 90° tilted angles from horizontal facing towards the south at various locations.

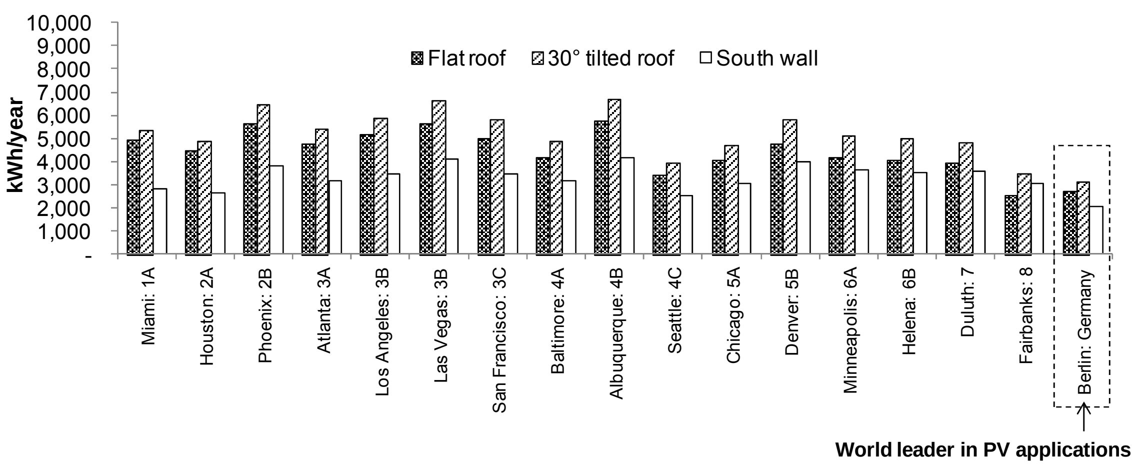


Figure 3. Annual PV electricity output from a 4 kW DC system in various locations calculated by PVWATTS 1.0.

Even though some locations such as Seattle and Fairbanks receive less solar radiation than other locations in the U.S., the solar radiation at both places is actually more than some areas of northern Europe, especially Germany, which is the world leader in PV applications. The successful utilization of PV systems tends to depend on energy management rather than the availability of solar radiation (Wassmer & Warner, 2006). PV panels also produce more electricity when the panels are cool than when they are hot, making it is possible for PV systems to perform better in colder climates. Some PV materials also perform better than others in diffuse light conditions.

Intermittency. Solar power is locally intermittent because of cycles of days and seasons. In a grid-connected PV system, the electric utility grid acts as an energy storage system (Figure 4). However, when the PV penetration rate is high in the future, energy storage systems are required for both small and large scale installations. Short-time intermittency because of clouds or weather conditions such as rain or storm also creates uncertainty in PV electrical production. Separating big plants from smaller plants or having systems placed on different buildings in the same complex can smooth this effect.

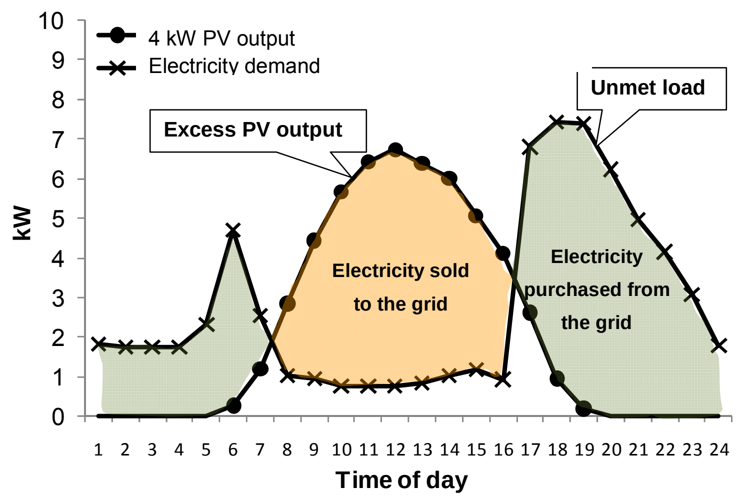


Figure 4. Hourly electricity demand graph shows how buildings can exchange electricity to and from the electric utility grids.

Grid support. The main concern with impacts from PV and other renewable energy power sources is that they have high output fluctuations. As more of these power sources are interconnected with power grids, various risks such as lower electric power quality and stability problems increase. These risks can be identified as overvoltage/undervoltage, instantaneous voltage change (sags/swells), voltage imbalance, harmonics, unintended islanding protection, short-circuit capacity, disconnection time for intersystem fault, DC offset, frequency fluctuation, supply security, and peak cut. Among these, dealing with overvoltage/undervoltage concerns is a top priority (Figure 5).

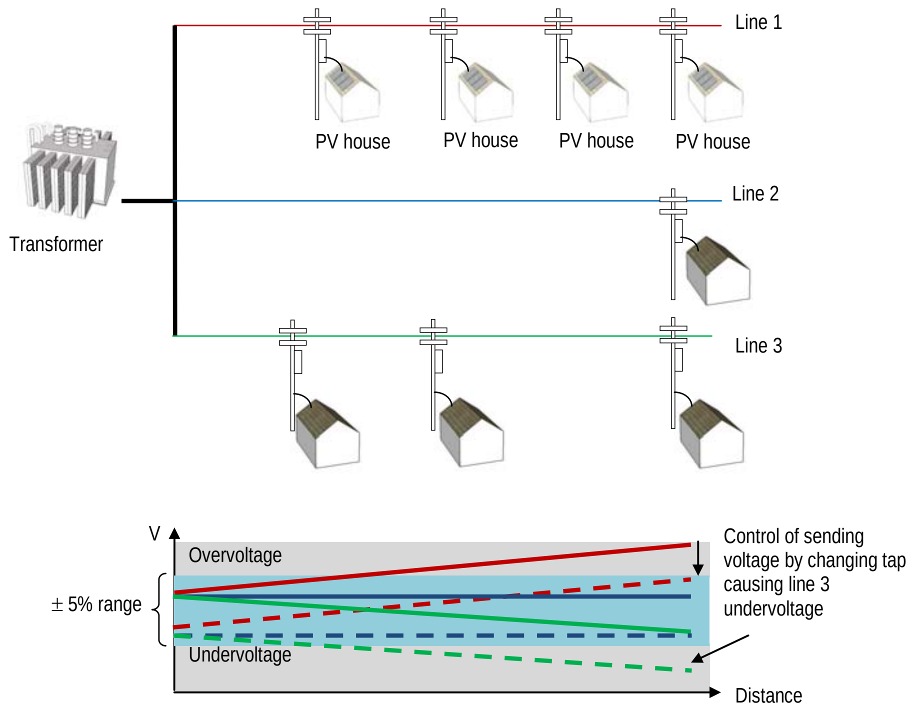


Figure 5. Conceptual diagrams showing when an overvoltage and undervoltage occurs in electric grids with building utilizing grid-connected PV systems (IEA PVPS Task 10, 2009).

Line voltage must be kept at certain levels to ensure reasonable distribution efficiency and proper operation of electrical equipment. The surplus electricity from the PV system could flow back to the transmission line and cause the voltage to rise above the upper limit, thus causing an overvoltage. It is possible to lower the sending output voltage from the transformer. However, this can also reduce the voltage of neighboring lines that go to the same transformer, causing an undervoltage.

High capital cost. For electrical consumers, electricity from photovoltaic systems typically costs more than traditional electricity options. However, depending on the location of the project, many incentives are available to help bring the investment cost down. Photovoltaic costs also have declined dramatically during the last decade and are likely to decline more in the future, while electricity prices are going up. PV systems also have other benefits, such as security in terms of no fuel cost and added value because of Time of Use (TOU) electricity rates, which are not addressed by a typical economic analysis.

1.4 Research Questions and Objectives

Matching PV electricity output with electricity demand can maximize a PV system's potential. However, in practice, sustainable buildings are usually designed to have the lowest energy consumption possible by incorporating various energy efficiency design strategies, and then renewable energy sources are simply added. Buildings might be designed to accommodate the installation of these systems, but there is no concern about how building energy loads resulting from each energy efficiency design strategy correlates with the electricity output from PV systems.

The majority of research in PV system optimization or potential analysis focuses on PV system configurations (Cheng, Sanchez Jimenez, & Lee, 2009; Denholm & Margolis, 2008; Mondol, Yohanis, & Norton, 2006; Pregelj, Begovic, & Rohatgi, 2002; Rohouma, Molokhia, & Esuri, 2007; Torrey & Kokernak, 2006), design integration with building façade (Jardim et al., 2008; Kiss & Kinkead, 1995; Yang & Lu, 2007), and system placements (Jardim, et al., 2008; Mondol, Yohanis, & Norton, 2007). Studies about the interaction between energy efficiency designs and PV electricity output are difficult to find, and thus, the effects are not well understood. The main emphasis in the building sector utilizing electricity from renewable sources, such as solar energy, is peak demand reduction and load shifting. The goal is to match PV electricity output with building load as much as possible. This will improve PV system efficiency by making the best use of solar when it is available, which will maximize the economic benefit and reduce grid stress. These benefits are PV system challenges stated in previous sections.

Buildings can be divided into three main categories: residential, commercial, and industrial. These buildings have different characteristics and need different strategies to deal with supply-demand matching (Figure 6).

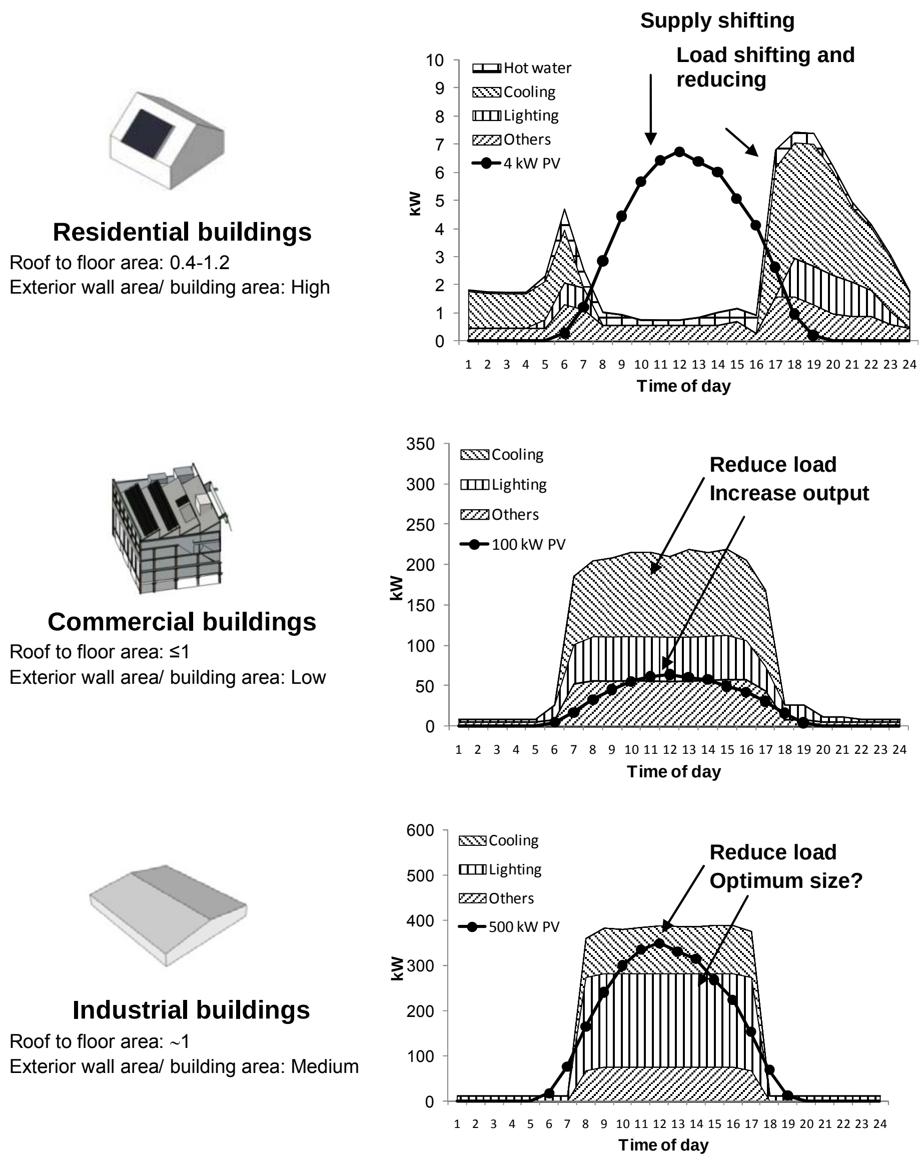


Figure 6. Characteristics and primary considerations in different building types for implementing grid-connected PV systems.

Research questions

- How can energy efficiency design strategies increase the amount of hours for which building loads are directly met by grid-connected PV system output? What are the best strategies that will achieve this increase? How do climate patterns, building types, patterns of building use, and grid-connected PV system size influence these interactions, and at what magnitude?
- How can electricity from grid-connected PV systems as individual buildings and as a group of buildings be effectively managed to benefit both building owners and electric utility companies?

Research objectives

- To understand the effects of climate patterns, building types, patterns of building use, and PV system size so that energy efficiency strategies can be prioritized to suit implementation in buildings with grid-connected PV systems in different conditions.
- To have an ability to manage the utilization of electricity produced from PV systems in different situations to maximize the benefit of being on grid.

1.5 Research Methodology

The main research strategy used in this study was an experimental method. This strategy sought to understand causality or causes and effects of each variable. Sets of building geometries and their characteristics, as well as PV systems installed, were systematically selected and modeled using a simulation tactic that replicated the building and PV system performance situation in a way in which it could give out measurable and useful data. In this controlled environment, various variables were tested and compared.

In this research, the setting was a computer simulation program. The independent variables were weather data, building types, building size, building use schedule, PV technology, and PV system size. Energy efficiency design strategies were intervening (mediating) variables. Dependent variables were building energy load, building energy profile, PV electricity output, and profile. This study compared the performance of PV systems in different scenarios. The outline of inputs and outputs in this study are shown in Figure 7.

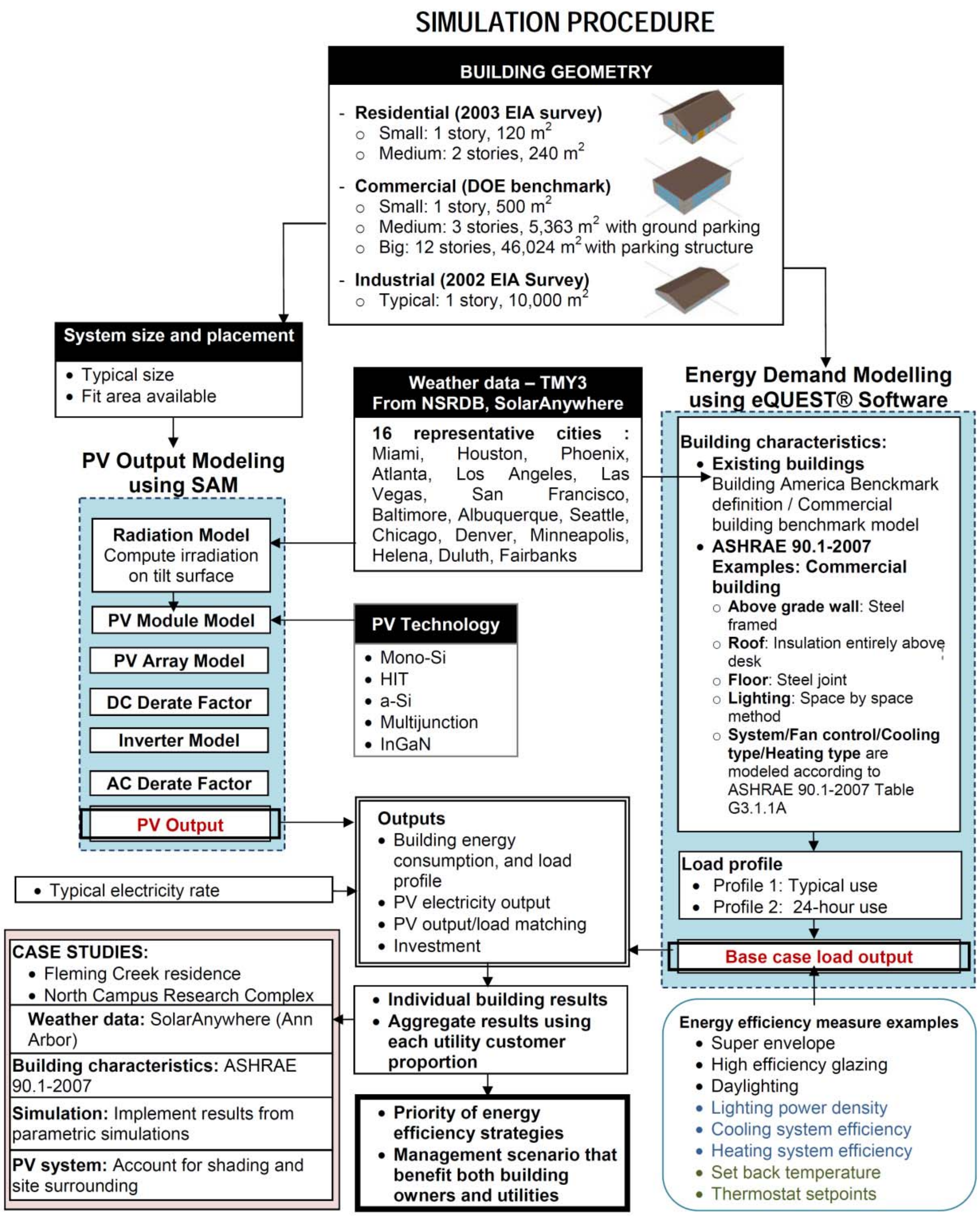


Figure 7. Flows of building energy simulation input-output in this study.

1.6 Outcomes and Contributions

With extensive simulation cases, a better understanding of the effects of energy efficiency design strategies on PV electricity output utilization was the expected outcome. Building design practitioners and building owners as well as electric utility companies – who are the expected audiences of this study – can select the best strategies that fit their objectives and budgets.

1.7 Organization of This Dissertation

This dissertation is organized as follows:

Chapter 1 summarizes the background and importance of the study, defines the objectives, research questions, and system structure of the study.

Chapter 2 describes building energy use characteristics, approaches to reduce building energy demands and building energy efficiency design strategies. The methodology used to model building stock as representative of existing buildings, buildings in compliance with energy codes, and buildings with implemented energy efficiency design strategies are presented.

Chapter 3 describes grid-connected PV systems and their potential in various building types according to their materials and sizes. Their impacts to the electric grid are also discussed.

Chapter 4 demonstrates the results of the simulations and their metric analyses.

Chapter 5 discusses the results and implications, draws conclusions about the key findings, and defines future works.

CHAPTER 2
BUILDING ENERGY EFFICIENCY DESIGN STRATEGIES AND BUILDING STOCK MODELING

Energy efficiency design strategies are most effective when building types and locations are taken into consideration. In this chapter, the U.S. building stock context is first discussed. Approaches to achieve energy efficiency buildings are introduced. Energy efficiency design strategies and their impact on building energy consumption, peak demand and load profile in different building types and climates are demonstrated. Building stock modeling details based on U.S. building stock characteristics and their energy savings when energy efficiency design strategies were applied in different climate zones are presented.

2.1 Building Energy Use Characteristics

In the U.S., the residential sector, comprised of 113.6 million households, accounts for the largest portion of the building sector energy use, followed by 4.9 million commercial buildings, and 0.2 million industrial buildings. As stated before, energy consumption in residential and commercial sectors accounts for more than 40% of the country's primary energy consumption. This energy demand is driven by economic growth, population growth, increasing building areas, real energy price, efficiency of energy used, and lifestyle. Since 1978, the U.S. Energy Information Administration (EIA) has conducted national energy consumption surveys in the building sector to collect data about nationally representative building characteristics and energy use behaviors. Currently, there are three types of databases in the building sector resulting from the following surveys: 1) Residential Energy Consumption Survey (RECS), 2) Commercial Building Energy Consumption Survey (CBECS), and 3) Manufacturing Energy Consumption Survey (MECS).

Trained interviewers were sent out to interview building occupants as well as to collect building information from statistically selected buildings. These data were then combined with data from energy suppliers to estimate energy use and cost. For MECS, online questionnaires were used. Data were collected approximately every three to four years. The results of each survey include several data tables, a microdata file, and several reports. The results are usually available to the public no later than two years after each survey.

2.1.1 Annual energy consumption.

Figure 8 shows the proportion of site energy end-use in cooling, heating, lighting, hot water, and other systems in residential, commercial, and industrial buildings. Details of these values from EIA national energy consumption surveys are shown in Table 1.

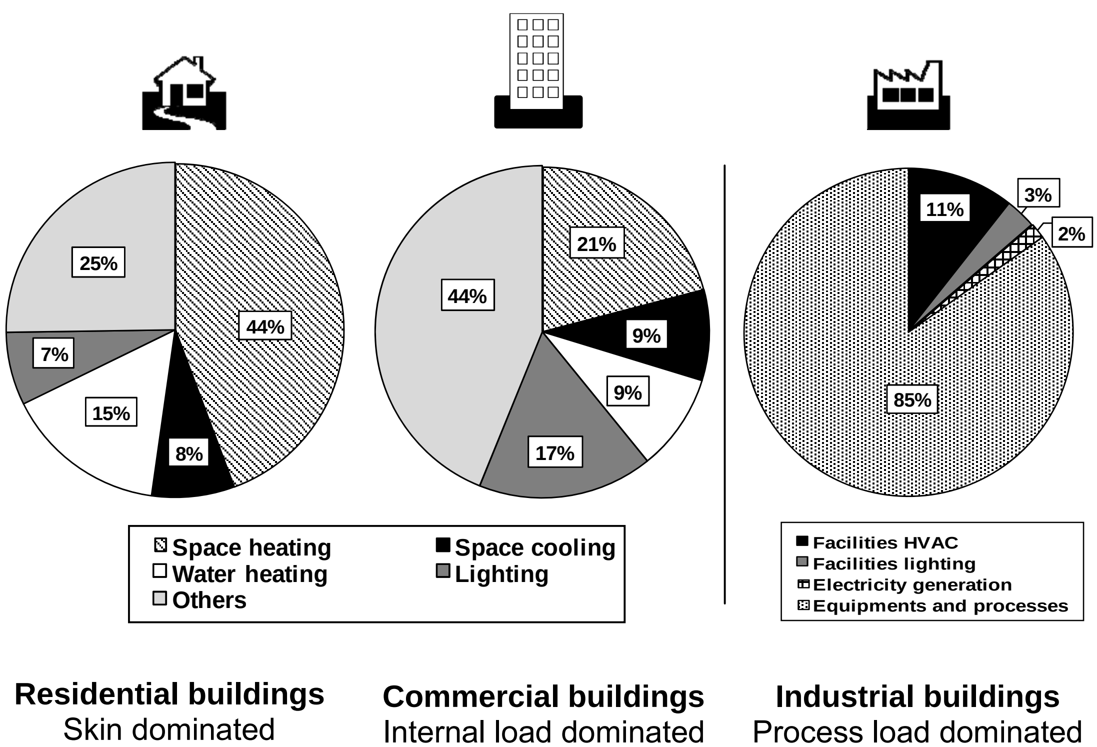


Figure 8. Site energy end-use proportion in each building type (EIA, 2005, 2006, 2007).

Table 1. Site energy end-use splits, by building type (EIA, 2005, 2006, 2007).

Residential buildings		Commercial buildings		Industrial buildings	
Categories	**%**	**Categories**	**%**	**Categories**	**%**
Space heating	44.3%	Space heating	20.9%	Facilities HVAC	10.6%
Space cooling	7.9%	Space cooling	8.8%	Facilities lighting	3.0%
Water heating	15.5%	Water heating	9.4%	Electricity generation	1.5%
Lighting	7.0%	Lighting	16.9%	Manufacturing and process loads	84.8%
Electronics	4.9%	Electronics	5.1%		
Refrigerations	4.4%	Refrigerations	2.8%		
Cooking	4.4%	Cooking	3.3%		
Computer	0.6%	Computer	2.6%		
Wet clean[1]	4.2%	Ventilation	4.6%		
Other[2]	3.2%	Other[3]	13.6%		
Adjust to SEDS[4]	3.5%	Adjust to SEDS[4]	12.1%		

[1]Includes cloth washer, cloth dryer, and dish washer.

[2]Includes small electric devices, heating elements, motors, hot tub and swimming pool heaters, outdoor grills, and natural gas outdoor lighting.

[3]Includes service station equipment, ATMs, telecommunication equipments, medical equipments, pumps, emergency electric generator, combined heat and power in commercial buildings, and manufacturing performed in commercial buildings.

[4]SEDS (State Energy Data System) is energy adjustment EIA uses to relieve discrepancies between data sources. It is energy use in residential building sector but not directly to specified end-use.

Each building type has different energy use characteristics. Residential buildings are small and have large proportion of envelope area to their floor area. Therefore, outside conditions have a high impact on the indoor atmosphere. The majority of energy is used for cooling and heating systems. In commercial buildings, the proportion of envelope area to floor area is small. Internal load from lighting and appliances, such as office equipment, personal computers, and refrigerators, is dominant. In industrial buildings, manufacturing loads or process loads are dominant. Excluding process loads, industrial buildings also use a large portion of energy for internal loads and have a larger proportion of this type of load compared with commercial buildings.

Energy consumption also varies from region to region largely because of local climates. The U.S. is located in the northern hemisphere, mostly between latitude 30°N to 48°N. Climate zones vary from hot and humid in Miami to very cold in Fairbanks. Data from EIA surveys can be grouped into four census regions (Figure 9). The average energy use in residential and commercial buildings located in each region is shown in Figure 10. Buildings located in the Northeast and the Midwest, which are the northern parts of the U.S., use more energy than buildings located in the southern and western parts primarily because of the need for heating in winter months. Figure 11 shows end-use energy split into space heating, space cooling, water heating, lighting, and refrigerator and other appliances. While energy use for appliances, lighting, and refrigerators, are quite constant across regions, space heating varies largely from the highest use in the northeastern region to the smallest use in southern region. Space cooling energy use is highest in southern region. However, the amount of energy use in space cooling is low compared with energy use in space heating in all regions. Buildings normally use natural gas for space heating and water heating systems. Electricity is then used for the rest of energy demand.

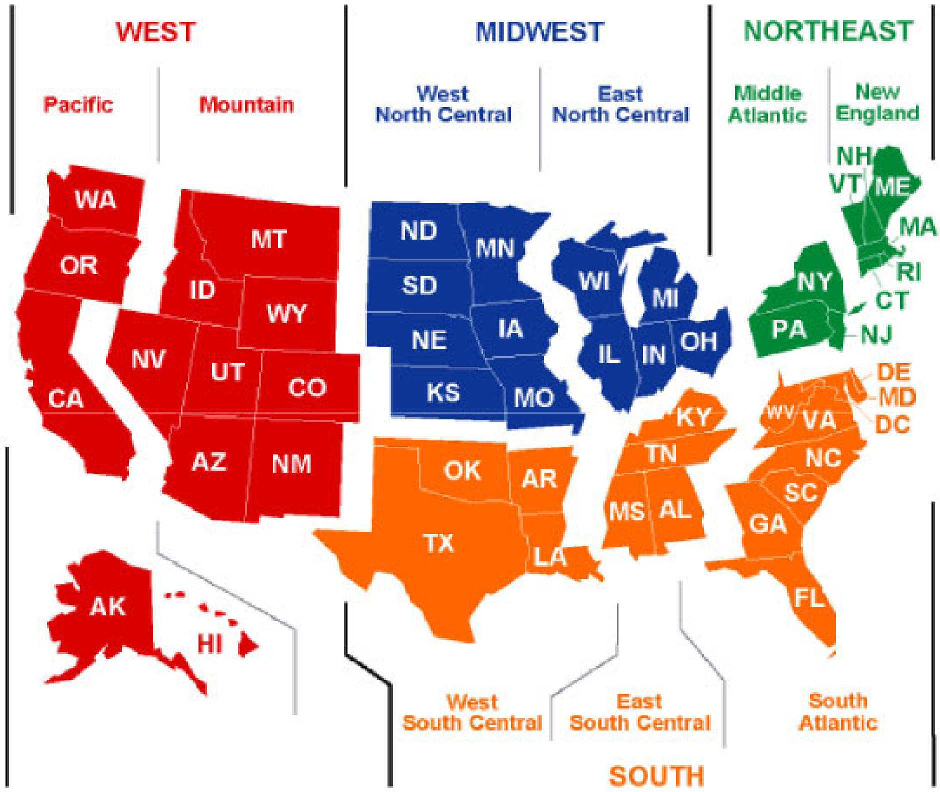


Figure 9. The U.S. census regions.

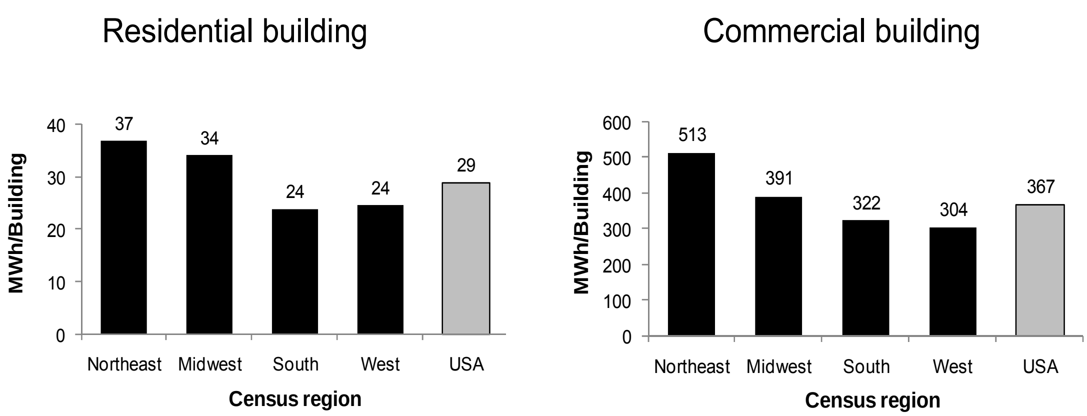


Figure 10. Residential and commercial building primary energy consumption, by census region (EIA, 2006, 2007).

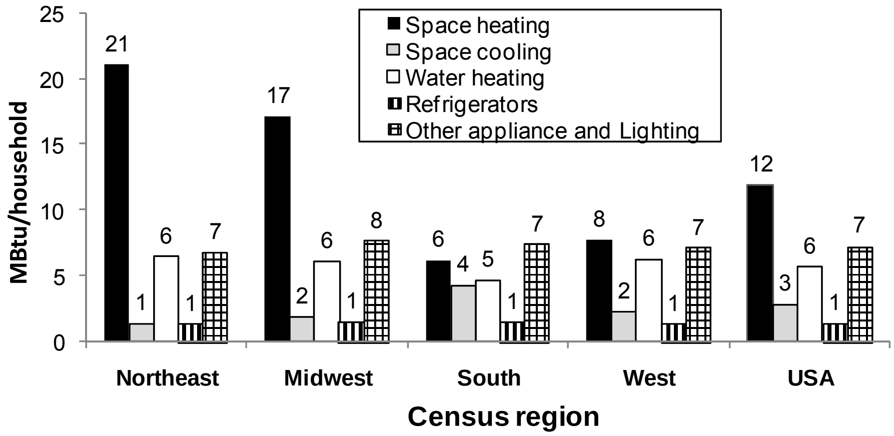


Figure 11. Residential primary energy end-use splits, by census region (EIA, 2007).

In residential buildings, how energy is used has changed substantially from the past. Residential buildings have become more energy efficient. The energy intensity per floor area has reduced. Energy used per household has dropped 31% since 1978; however, building size has become larger with fewer occupants. The number of electronic appliances has increased significantly. Energy consumption from electronic appliances has almost doubled between 1978 and 2005, partly offsetting the energy saving from using high efficiency heating systems, high efficiency cooling systems, or better envelopes.

In commercial buildings, electricity accounts for more than half of the energy consumed in the whole sector. Within a building, space heating and lighting generally consume more than half of the total energy consumption. Natural gas demand and electricity demand used to be nearly equal in 1979. In the 2003 survey, electricity had increased while natural gas declined and the proportion of electricity consumption to natural gas consumption was 5:3. Even though commercial building floor space increased, the energy intensity has remained nearly constant, indicating more efficient commercial buildings have been built in the last decade.

Industrial buildings also experienced energy intensity reduction because of the growth in on-site energy generators and efficiency improvements in manufacturing processes. Overall, even though building electricity consumption is projected to increase by 16% in 2035, the energy demand increasing rate is moderate comparing to population growth and building area increasing rate. The energy per capita is decreasing as a result of the improvement in appliance efficiency and building envelopes. In the Energy Outlook 2011 (EIA, 2011a), EIA suggested that expanding household appliance energy standards could help significantly reduce this portion of energy consumption. Another mechanism that has been used to successfully reduce building energy demands is implementing building energy codes.

2.1.2 Annual peak demand.

Peak demand is the highest energy power consumed during a specific time period. Electricity peak demand is of concern in this study. Normally, a building's peak electricity demand occurs during a hot afternoon in the summer months when air-conditioning system loads are the highest. Peak demand forces electric utility companies to invest in higher capacity transmission systems and to build more power plants that may only run during peak load demand periods, thereby influencing peak electricity rates. Electricity utility companies usually penalize buildings that do not carefully use their electricity and create over-all peak demand. Building load profiles vary greatly because of building types, geometries, locations, and patterns of use.

Figure 12 shows the impact of building types, use patterns, and weather zones on electrical building load profiles generated by computer simulations. Residential buildings usually have peak demand in the morning and evening when people come back from work. On the other hand, commercial and industrial buildings have peak load demand during the day. All three types of buildings with typical use schedules have higher electricity demand in the afternoon or evening as compared with the morning period. This is because heat transfer into the buildings is normally stronger in the afternoon because some portion of solar radiation that has been absorbed into the environment is released as heat during the latter part of the day more than in the morning. Normally, commercial buildings are the driver of overall peak load profile for electric utility companies. Figure 13 shows an example of daily utility load profiles in a summer month. In areas where peak loads are much higher than normal load profiles, peak demand charges or different utility rates are often used to encourage buildings to use energy at other times.

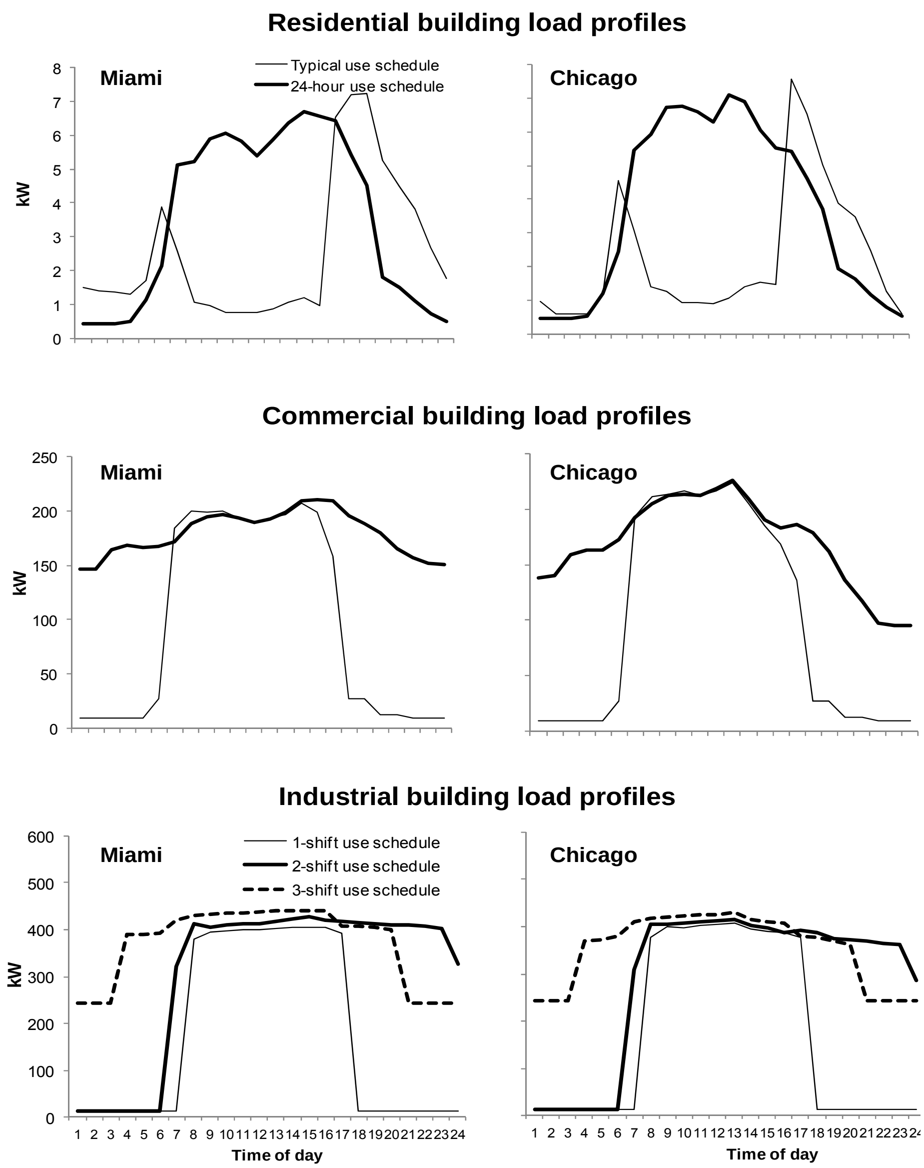


Figure 12. Simulated load profiles on peak summer days in Miami and Chicago.

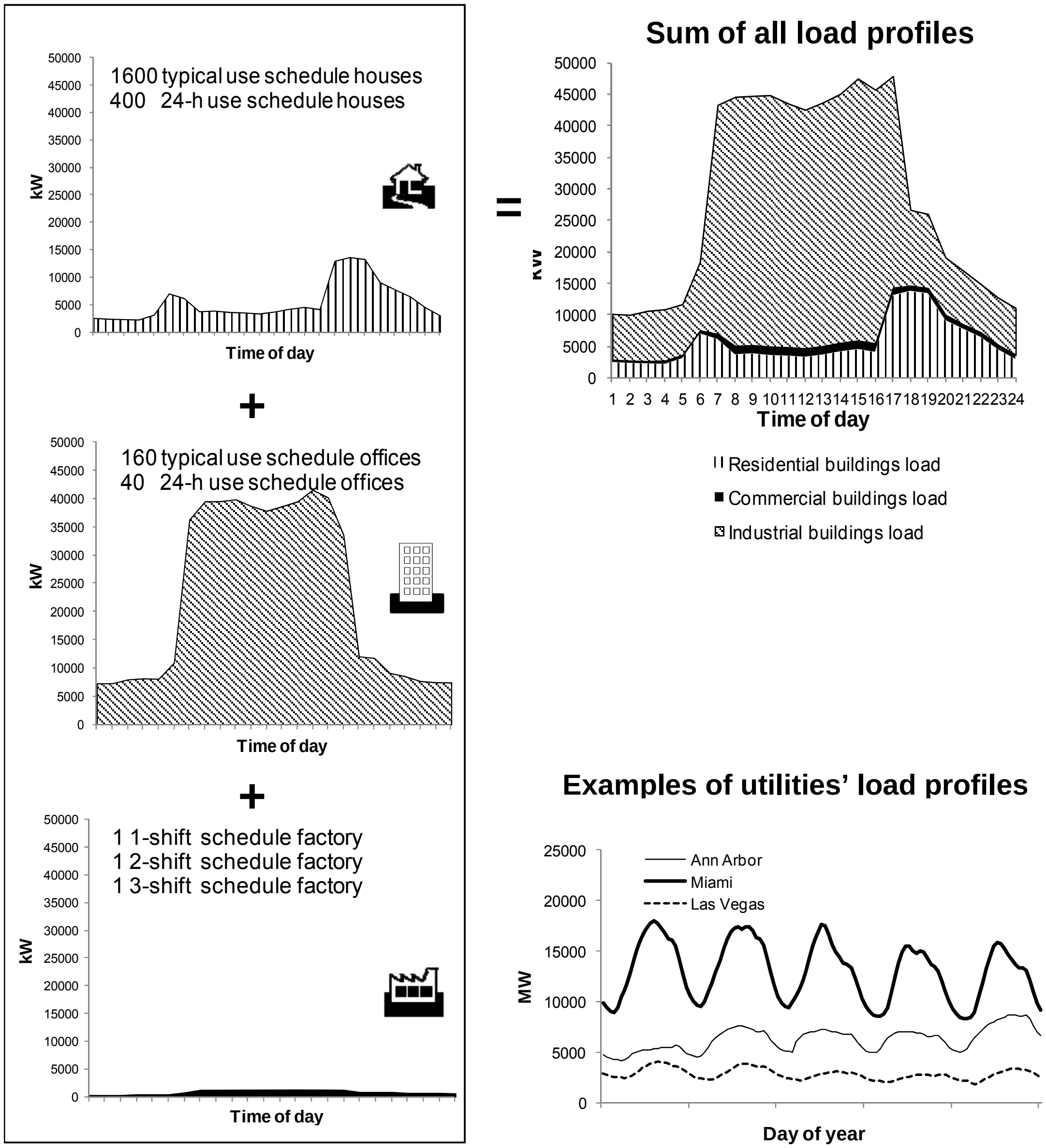


Figure 13. An example of utility daily load profiles in Chicago on a summer day and examples of utility load profiles in selected cities.

2.2 Approaches toward Energy Efficiency Buildings

2.2.1 Climate analysis.

Climate is the first factor to consider when designing energy efficiency buildings. In the past, when there was no mechanical system and electricity available, buildings were designed with respect to local climate to provide maximum indoor comfort to its occupants. The availability of electricity allowed the use of lighting, heating, ventilation, and air-conditioning systems which enabled a building to stay within a thermal comfort zone without the need to consider the local climate. However, buildings that are designed without climate consideration are likely to use more energy to maintain acceptable conditions for their occupants. Many pre-design tools involving local climate analysis have been developed to help architects design buildings appropriate for each climate zone. A very popular tool is a bioclimatic chart with many versions such as Olgyay's Bioclimatic Chart (Olgyay & Olgyay, 1963) and Givoni-Milne's Bioclimatic Chart (Watson, 1978). One example of this tool is shown in Figure 14. In this chart, temperature and humidity are plotted onto predefined areas which will indicate appropriate design strategies for given locations. With these tools, weather data are characterized and appropriate design strategies utilizing natural energy resources and minimizing energy consumption are generated.

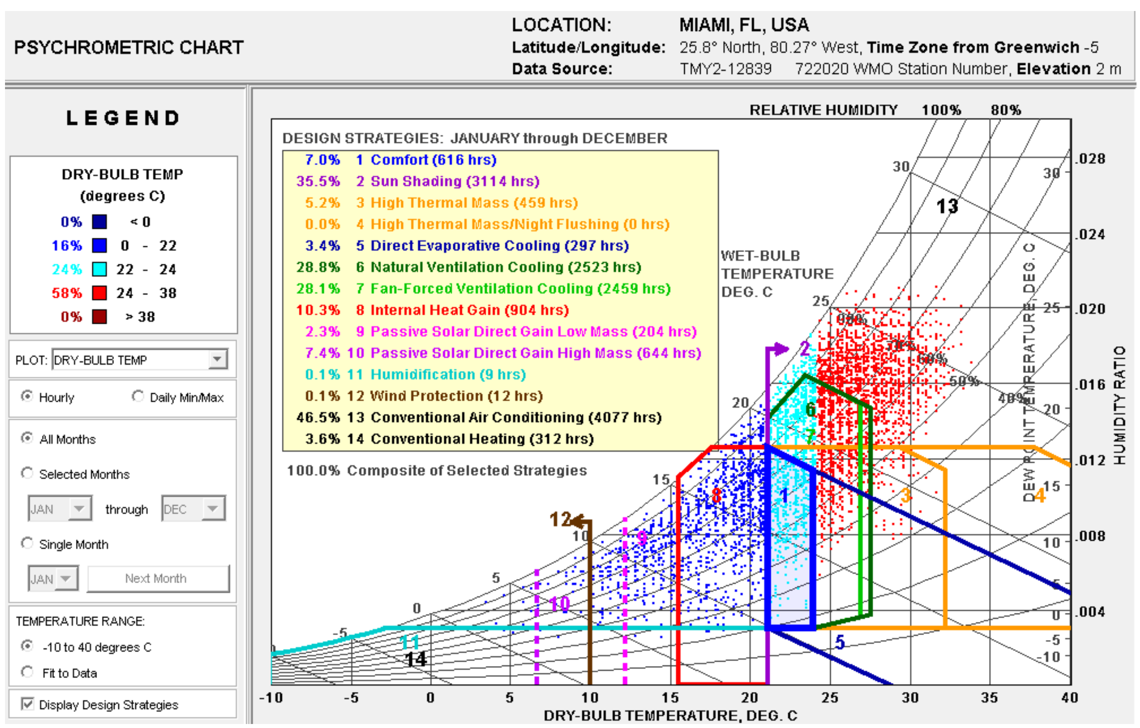


Figure 14. Miami's psychrometric chart generated by Climate Consultant indicates that, to maintain thermal comfort, buildings at this location need shading, ventilation, and air-conditioning systems.

2.2.2 Compliance with codes and standards.

As discussed in chapter 1, every state in the U.S. has adopted energy codes or energy standards to provide minimum requirements for building components and systems. This process ensures a certain level of energy efficiency in buildings. The ASHRAE 90.1 and the IECC are the most common two standards and codes adopted.

The ASHRAE 90.1 was first released in 1975. Revised editions were published in 1980, 1989, and 1999. Starting with the 2001 version, the standard has been updated and published every three years. The latest version is 2010. The ASHRAE 90.1 provides minimum energy efficiency requirements for new construction, new portions of buildings, and new systems in existing buildings. The provisions of these standards apply to 1) envelopes of conditioned and semi-conditioned spaces, 2) heating, ventilating and air conditioning systems, 3) service water heating, 4) electric power distribution systems, and 5) lighting systems. The current standard provides eight sets of envelope requirements based on climate zones as indicated in ASHRAE 169-2006—Weather Data for Building Design Standards (American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc. [ASHRAE], 2006b). Seven of these climate zones except for the subarctic (which is Alaska), are shown in Figure 15. These climate zones are characterized based on a Heating Degree-Day base of 18°C (HDD18) for the heating and Cooling Degree-Day base of 10°C (CDD10) for the cooling. These climate zones are further subdivided by moisture levels into moist or humid (A), dry (B), and marine (C).

ASHRAE has released a separate standard called ASHRAE 90.2 Energy-Efficient Design of Low-Rise Residential Buildings (ASHRAE 90.2) (ASHRAE, 2007b) which is applicable to residential buildings three stories or less above grade. The original ASHRAE 90.2 was first published in 1993. The latest version currently is 2007.

The IECC was first released in 1998, with the 2009 release as the latest version. It has separate sections covering both commercial and residential buildings. The provisions are similar to those of ASHRAE 90.1 and 90.2. It also recognizes the same eight climate zones as in ASHRAE 90.1.

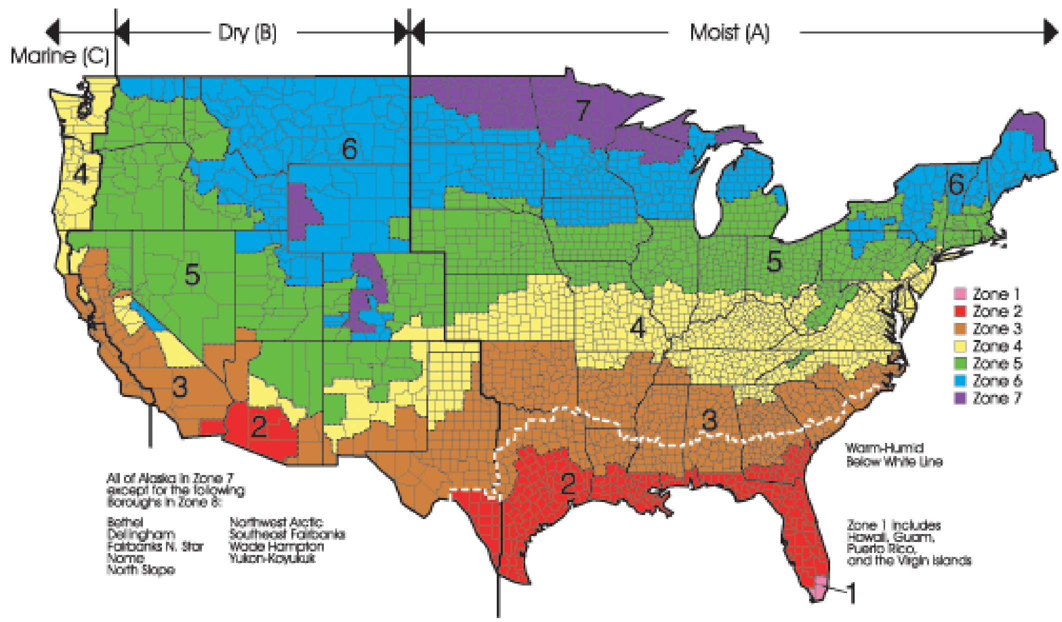


Figure 15. The U.S. climate zone map (ASHRAE, 2006b).

Generally, energy standard requirements consist of:

- Envelope requirements based on climate zones; for example, exterior surface solar reflectance, thermal resistance value (R) or thermal transmittance (U) for wall, floor, roof, and glazing. For glazing requirements, additional solar heat gain coefficients (SHGC) or shading coefficients (SC) are also specified.
- Minimum HVAC system efficiency, thermostat setpoint, economizer requirements, system supply temperature reset, ventilation rate, infiltration rate, air leakage rate, fan power limitation, energy recovery requirement, duct insulation R-value.
- Maximum Lighting Power Density (LPD).
- Minimum service water heating efficiency.

- Minimum requirement in building power distribution system.

There are three options to comply with both the ASHRAE 90.1 standard and IECC code. They are prescriptive, trade-off, and performance-based approaches. The prescriptive approach lists requirements for each building component and system. This approach is easy to follow: the requirements must be met exactly as specified. The trade-off option allows buildings to increase efficiency in one component or system in exchange for a decrease in another. The performance-based approach is the most flexible option. This approach allows buildings to compare their overall energy performance with the baseline building meeting the minimum requirement set by codes or standards. However, a performance-based approach needs a higher degree of understanding of how building components interact with systems and outdoor conditions.

Going beyond baseline codes is possible with beyond-code programs. These programs are often built upon baseline codes such as IECC and ASHRAE 90.1, but with higher standards of levels of requirements. Some offer more details and explanations of implementations. Local governments might allow compliance with these beyond-codes in exchange for incentives. Examples of these guidelines are as follows:

Advance Energy Design Guides (AEDGs): ASHRAE, with support from the Department of Energy (DOE), and in collaboration with the American Institute of Architects (AIA), the Illuminating Engineering Society of North America (IES), and the U.S. Green Building Council (USGBC), has developed the Advance Energy Design Guides (AEDGs) for six commercial building types representing the majority of the commercial building sector. These commercial building types are small hospital and healthcare facilities, highway lodgings, small warehouses and self-storage buildings, K-12 school buildings, small retail buildings, and small commercial buildings. The guides offer energy efficiency design strategies needed for achieving a 30% energy savings compared with buildings that comply with ASHRAE 90.1-1999 in each climate zone. The guides can be downloaded from the ASHRAE website at no charge. Recently, ASHRAE has released 50% energy savings compared with buildings that comply with ASHRAE90.1-2004 for small to medium office buildings, retail buildings and K-12 schools. Large hospitals 50% energy saving design guide will be released soon.

ENERGY STAR: ENERGY STAR is a joint program of the U.S. Environmental Protection Agency (EPA) and the U.S. DOE. The program provides sources of qualified energy efficient products and services information as well as the ENERGY STAR certified program for residential and commercial buildings. ENERGY STAR qualified homes achieve energy savings through established, reliable measures. Building owners work with qualified home energy raters in order to rate the technologies to apply to the houses. Below are features of an ENERGY STAR qualified home:

- Good insulation,
- High-performance windows,
- Tight construction and ducts,
- High efficiency heating and cooling systems,
- High efficiency lighting and appliances, and
- Third-party verification.

ENERGY STAR qualified buildings are those that use less than 75% of the energy of an actual building in the same category. Unlike the common practice that a building is designed to exceed the minimum set of requirements in a reference building defined by energy code, ENERGY STAR uses real world building energy consumption as a benchmark for the energy reduction target, indicating how a building performs relative to other similar buildings.

Building America: The Building America research program has been developed by the U.S. DOE Residential Buildings Program and the NREL in consultation with the Building America industry team. The goals are to provide market-ready energy solutions for new and existing homes in each U.S. climate zone which help reduce energy use at least 40 to 70% when compared with IECC 2009 compliant buildings and the use of on-site renewable power production of up to 30% of building energy consumption. The Building America program provides both resources and prices for residential energy efficiency solutions. Technical support guides for whole-house energy savings are available for buildings located in climate zones that are: (a) mixed-dry, hot-dry, and marine; (b) mixed-humid and hot-humid; and (c) cold and very cold. Building America recognizes seven climate zones as shown in Figure 16.

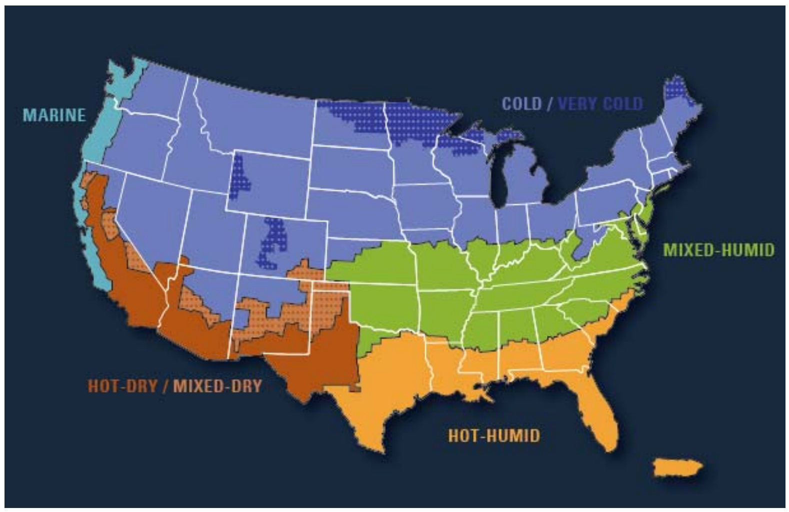


Figure 16. Climate zones recognized by Building America (U.S. Department of Energy [U.S. DOE], 2010a).

Core Performance Guide: The Core Performance Guide developed by the New Building Institute (NBI), outlines a prescriptive approach to achieve 20% to 30% energy savings in small to medium commercial buildings when compared with ASHRAE 90.1-2004 compliant buildings (New Building Institute, 2007). The guide is a nationally recognized resource. More than 30 criteria are used to define a high performance building, including provision of building envelope, heating, ventilation and air conditioning systems, lighting, and power systems and controls.

Leadership in Energy and Environmental Design (LEED): LEED is a sustainable building rating program developed by the U.S. Green Building

Council (USGBC) to provide building owners and designer teams a framework for identifying and implementing sustainable building design practices that are practical and measurable. There are several metrics used such as sustainable site, water efficiency, energy and atmosphere, materials and resources, and indoor environmental quality. Energy savings have the highest score proportion because of the extensive environmental impact compared with other metrics. The LEED certified program is comprised of several rating systems: new construction, existing buildings, homes, and neighborhood development. For commercial buildings, LEED-NC version 3.0 adopted ASHRAE 90.1-2007 Appendix G: Performance Rating Method as a benchmark for its Energy and Atmosphere Prerequisite 2 (EAp2) and Credit 1 (EAc1). Buildings that can reduce energy use compared with the ASHRAE 90.1-2007 requirement, will get as high as 35 points accounting for 32% of total LEED points for new construction. Small and medium buildings can also follow the Core Performance prescriptive approach in order to earn points, but in fewer portions as compared with performance based approach. For homes, LEED offers both a performance-based approach using ENERGY STAR for homes as a benchmark, as well as prescriptive design approaches for each building component.

2.2.3 Building management system (BMS).

The availability of computers makes it possible to automatically control building operations. This is useful especially in large buildings involving multiple systems and factors. Building Management Systems (BMS) utilizing computer based software to compromise building energy demand are most common in large buildings. Energy efficiency improvement from BMS include heating, ventilating and air conditioning (HVAC) system controls, optimum start stop, demand limiting (load shredding), duty cycling, power fail auto restart, and fan and damper control. These systems represent approximately 40% of building energy use. If the lighting system is included, BMS would manage approximately 60% of a building’s load. Commissioning the system is critical as improper use of BMS may result in no reduction in energy consumption.

2.2.4 Building energy simulation.

The performance of a building is a result of complex processes. Barriers to achieving energy reduction through innovative energy efficiency design are usually not technological constraints, but poor data availability to make informed decisions (Clarke, 2001). Building simulations are created to help provide real world replication and predict how buildings and systems will perform once they are constructed and implemented, thus providing information for decision making. Design tools have evolved from traditional manual methods such as bin and degree day methods. Interactions between building, components, systems, and climatic conditions are complex and beyond the scope of hand calculations. Today, building energy performance prediction tools use computers as platforms and are comprised of a series of complex mathematical models trying to trace energy flow paths and address the dynamic interaction of building and system performances with building geometry, plan, components, system choices, climate conditions, and occupant use patterns.

Energy simulation is an important tool for going beyond baseline codes as suggested in the previous section. To predict how buildings are going to behave with each design strategy, computer simulation has been used to aid these design decisions. ASHRAE 90.1 appendix G Performance Rating Method section G2.2.1 listed eight criteria as requirements for acceptable energy modeling tools. These tools must be able to handle 10 or more thermal zones, generate hourly data for 8,760 hours/year, account for thermal mass effects, model part load performance curve, model capacity and efficiency correction curve for mechanical heating and cooling, model air-side economizers with integrated control, and accommodate hourly variation in occupancy, lighting power, equipment power, thermostat setpoints, and HVAC system operation defined separately for each day (ASHRAE, 2007a). ASHRAE 90.1 appendix G Performance Rating Method section G2.2.4 also states that the simulation tool shall be tested in accordance to ASHRAE standard 140 by the software provider.

Lists of qualified building simulation programs for tax deduction purposes can be found at http://www1.eere.energy.gov/buildings/qualified_software.html.

2.3 Energy Efficiency Design Strategies

Building energy loads can be divided into non-weather dependent loads and weather dependent loads. Examples of non-weather dependent loads are from appliances and lighting. To reduce non-weather dependent load, efficiency improvement is the main target. This type of load can also be reduced by decreasing the operation time with various techniques, for example, using occupancy sensors to turn some appliances off when there is no user for a specified time period and using lighting level sensors to lower lighting intensity when daylighting is available. Examples of weather dependent loads are cooling, heating, and water heating. Lowering this type of load is more complicated and needs different strategies in different weather zones. Strategies used to reduce space heating loads include reducing heat transmission loss and infiltration loss by designing a well-insulated and tight building envelope, using passive solar heat gain, and recovering heat from exhausted air. Strategies used to reduce space cooling load are preventing summer solar heat gain through opening, preventing heat transfer into buildings by designing well-insulated and tight building envelopes and using other precooling strategies such as night ventilation and ground ventilation cooling. Automatic operation adjustment or shutdown and temperature set back control are used to reduce load-hours in heating and cooling systems. For water heating systems, strategies used include reducing demand by using low flow fixtures, improving system efficiency, and using solar hot water systems.

There are multiple databases on energy efficiency design strategies available from agencies such as the U.S. DOE (U.S. DOE, 2012b), the IEA (International Energy Agency, 2012), and the WBDG (Whole Building Design Guide, 2012). Since the 1970’s energy crisis, the U.S. government has sponsored many research projects in order to gain more understanding on using appropriate energy efficiency design strategies for each building type located in each climate zone. Computer simulation tools were heavily used to explore the complex trade off of results from design strategies. For example, glazing with lower transmittance coefficient helps reduce solar radiation entering buildings during the summer, which can reduce cooling load, but on the other hand, it allows lower heat gain in winter, increasing heating load and reducing daylight entering buildings resulting in the increased need for electric light.

This study used major energy efficiency design strategies selected from the literature that were proven to have high impact on energy reduction for typical buildings. They are mostly applicable in new buildings or major renovations and can be easily modeled with energy modeling software. These strategies are grouped into architectural components, building systems, building management, and combinations of strategies.

2.3.1 Architectural components.

a) Super-insulation.

Super-insulation refers to buildings with insulation of opaque walls and roofs and air tightness levels significantly exceeding local building codes. Joists inside wall and roof structures that can interrupt the continuity of insulation and result in heat transfer hot spots called thermal bridges are carefully covered by insulation. The level of building insulation is usually specified using two properties, R-value and U-factor. Thermal resistance or R-value (m^2K/W or $h·ft^2·°F/Btu$) is a material property commonly used when a specified level of insulation is needed. R-value is how much the insulation is resistant to heat flow. The higher the R-value, the more the material insulates. Another property of wall assemblies used to meet a specified level of heat transfer of the entire wall section is called U-factor (W/m^2K or $Btu/h·ft^2·°F$) or thermal transmittance. U-factor is the rate of heat transfer through one square meter of a structure divided by the difference in temperature across the structure. Outside and inside air film effects are included in the calculation for U-factor. The lower the U-factor, the better that wall assembly can resist the heat flow.

The amount of insulation in a super-insulation envelope depends on climate. Typically, a super-insulation envelope has a U-factor (Hestnes, Hastings, Saxhof, & International Energy Agency, 2003). Many projects use an R-value at 7.044 m^2K/W or 40 h·ft²·°F/Btu (R40) for walls and 10.566 m^2K/W or 60 h·ft²·°F/Btu (R60) for roofs in order to reach super-insulation condition. When insulation levels increase, wall thickness is also increased and might affect the interior space. Low conductivity material should be used for wall insulation to minimize interior space loss. However, raising the insulation level above a certain point may have negative impacts on a building with high internal load because heat cannot easily dissipate from the building to the outside, which will result in higher cooling load.

b) High-performance windows.

High performance windows are window systems that have a U-factor at 1.5 W/m^2K or lower (Hestnes, et al., 2003). This can be achieved with two or more glazing panes filled with inert gas and with a low-e coating. In addition, high performance windows should have high visible light transmission and low air leakage. In cold climates, it is preferable that solar transmittance is not lower with a low-e coating so that winter sunlight can be admitted into the building, while for hot climates, solar transmittance should also be low. Solar transmittance is usually indicated by the Solar Heat Gain Coefficient (SHGC). SHGC is the fraction of incident solar radiation admitted through a window system including the effect of the window frame. The window frame's heat transfer can be reduced by using low conductivity materials. ENERGY STAR requirements for resident high-performance windows version 5.0 are shown in Figure 17.

Climate zone	Fenestrations U (W/m^2K)	Fenestrations SHGC	
Northern	≤1.70	Any	**Prescriptive**
	≤1.76	≤0.35	Equivalent energy performance
	≤1.82	≤0.40	
North-central	≤1.82	≤0.40	
South-central	≤1.99	≤0.30	
Southern	≤3.41	≤0.27	

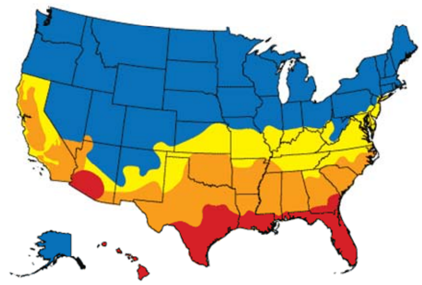


Figure 17. ENERGY STAR zones for window specifications (U.S. Green Building Council, 2009).

c) Thermal mass.

The ability of material to store heat can help by decreasing indoor temperature swings. To create thermal mass, heavy materials such as block, concrete, stone, or brick are used. Heat is stored in these thermal masses during over-heated periods and released later during under-heated periods. Figure 18 shows an example of indoor temperature behavior of a building with high thermal mass compared with outdoor ambient temperature and indoor temperature of the same building with low thermal mass. This behavior results in thermal mass ability to shift and reduce peak electricity demand.

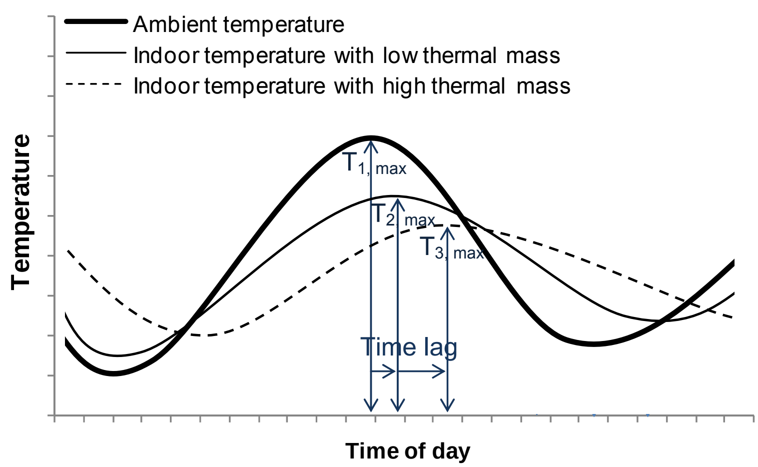


Figure 18. Heat transfer into buildings is partly stored in the building materials. The higher the thermal mass, the greater the time lag from the highest temperature inside the building to the smallest indoor temperature.

Thermal mass is not suitable for hot weather especially in tropical climates where there is no cool outdoor temperature period. In this climate type, using thermal mass will prolong uncomfortable temperatures. Tropical architecture needs light construction so that heat during the day can be quickly released to the atmosphere when the day ends.

d) Daylight harvesting.

Daylight harvesting – or daylighting – is a strategy that makes use of natural light during the day when it is available in order to reduce artificial lighting energy consumption. This strategy can work automatically with the use of sensors to detect the level of lighting with electric lights dimmed or turned off in response to the presence of natural light (Figure 19).

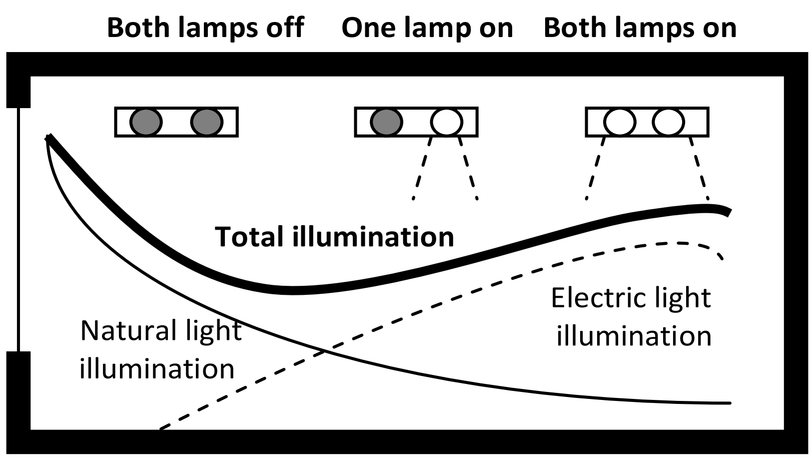


Figure 19. Daylighting sensors detect natural light level and adjust artificial light on-off accordingly.

Daylight harvesting is possible when building envelopes are designed to accommodate natural light entering buildings. This can be accomplished by allowing enough openings in the wall or by using skylights (Figure 20). However, preventing direct sunlight from entering building is important. Direct sunlight might create glare problems as well as too much heat accompanying it. Light shelves and suncatchers can be used to redirect direct sunlight into buildings.

Each climate zone has different sky conditions and weather patterns. Therefore, design strategies to accommodate natural light while preventing direct sunlight are different. For example, in regions with mostly cloudy skies, direct sunlight prevention is not important and openings should be located high on the wall to capture reflected light coming from the ground. In regions with sunny skies, light shelves should be used to prevent direct sunlight while allowing reflected light into buildings (Figure 21).

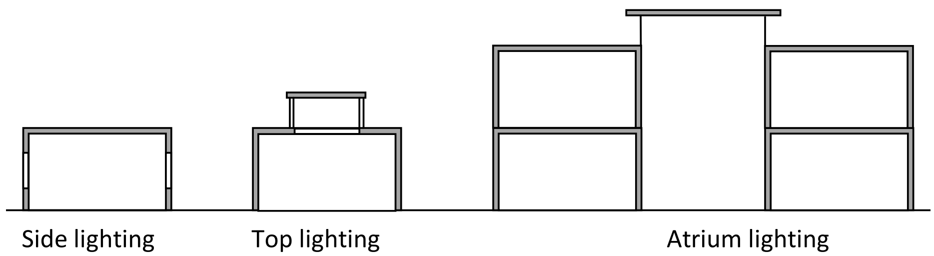


Figure 20. Typical strategies used to bring natural light into buildings.

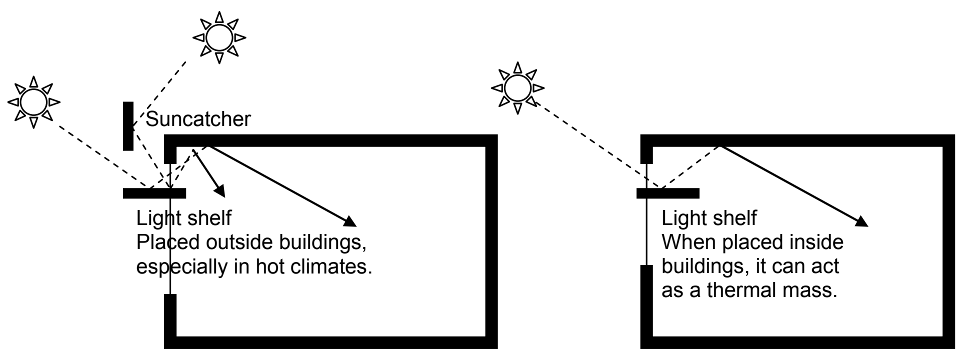


Figure 21. Side lighting strategies in different climates.

Detailed design can help maximize natural light use in buildings. Some examples of this include the height and the placement of openings, exterior and interior shading devices to prevent and redirect sunlight, ceiling slope to help reflect natural light deep into the building, furniture placement, choices of interior finish and colors (Figure 22), as well as advanced daylighting systems such as daylight collectors, light pipes, light wells, or special shading device such as micro-louvers, OKASOLAR system and solar ducts. However, these designs are unique to each project; therefore, they are not investigated in this research. The simulations of their performances are also beyond the capabilities of the software used in this study.

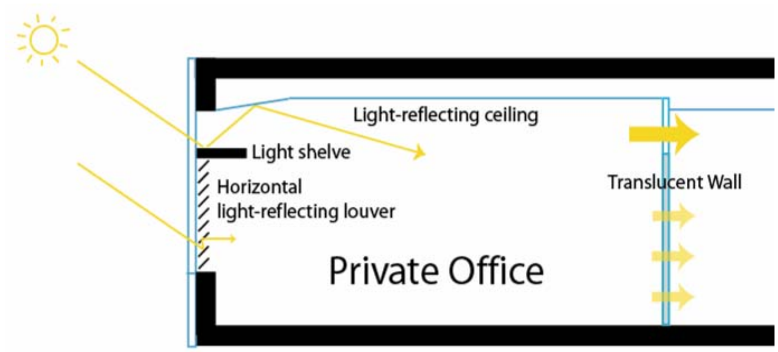
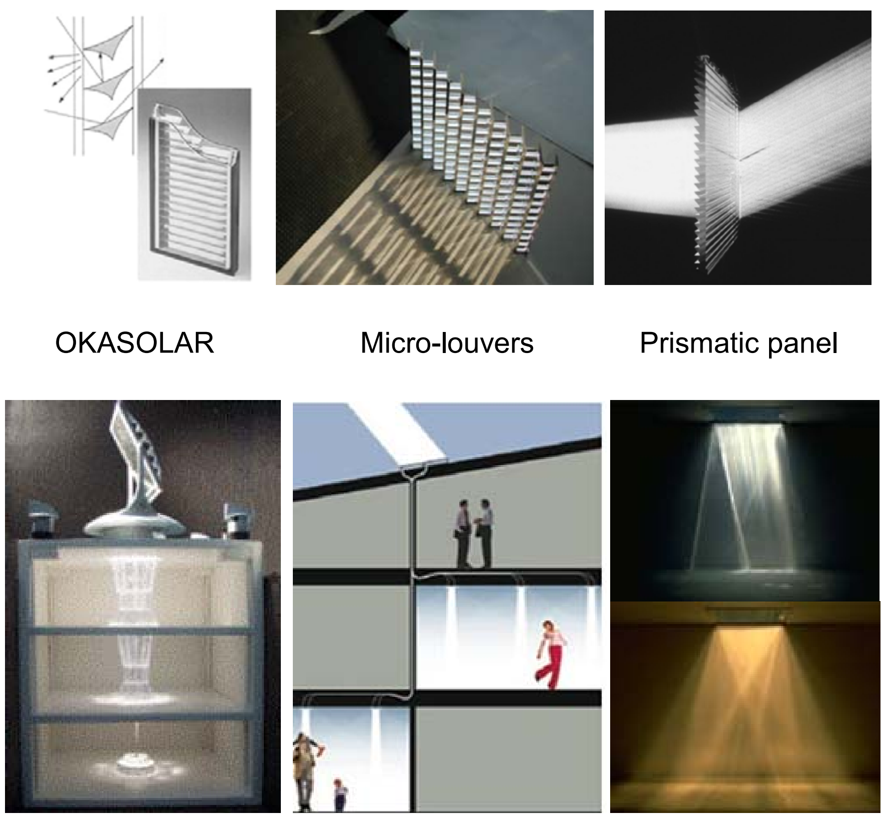


Figure 22. Daylight harvesting design strategies letting natural light deep into the space using light colored materials, transparent or translucent materials, and architectural elements.



OKASOLAR Micro-louvers Prismatic panel

Solar duct Daylight collectors Light chimney

Figure 23. Advanced shading and daylighting systems.

Artificial light dimming may be accomplished using either stepped or continuous controls. Stepped control is often recommended for spaces with non-working space, such as lobbies or corridors. Continuous dimming is often recommended for spaces where people are working, like office spaces. Advanced dimming technologies, using individually addressable ballasts and wireless technology, are also available. In addition to energy savings, daylighting generally improves occupant satisfaction and comfort. Windows also provide visual relief, a contact with nature, time orientation, the possibility of ventilation, and emergency egress.

2.3.2 Building systems.

e) Cooling system efficiency.

Two-thirds of all homes in the United States have air conditioners. Air conditioners use about 5% of all the electricity in the U.S. Using high efficiency cooling systems can reduce electricity used in this section by 20% to 50%. Performances of cooling systems can be indicated by cooling efficiency such as the Energy Efficiency Ratio (EER), Coefficient of Performance (COP), or Seasonal Energy Efficiency Ratio (SEER). EER and SEER both are the ratio of cooling output in Btu/h to the input electricity in W, but EER is measured at maximum cooling load condition while SEER is measured using typical weather conditions at a specific location throughout the year. SEER is becoming more popular and is a better indicator of cooling system performance. COP is similar to EER but unit-less because it is the ratio of cooling output to the input electricity using the same unit (W to W or Btu to Btu) at the spontaneous time. SEER is generally a higher value than EER for the same equipment. Typical EER for residential central cooling units are equal to 0.875 × SEER. A more detailed method for converting SEER to EER uses this formula: $EER = -0.02 \times SEER^2 + 1.12 \times SEER$. A SEER of 13 is approximately equivalent to a COP of 3.43, meaning that 3.43 units of heat energy are removed from inside the building per unit of work energy used to run the heat pump.

SEER rating more accurately reflects overall system efficiency on a seasonal basis and EER reflects a system's energy efficiency at peak day operations. Both ratings are important when choosing products. As of January 2006, all residential air conditioners sold in the United States must have a SEER of at least 13. ENERGY STAR qualified central air conditioners must have a SEER of at least 14. Residential split-system air conditioners of SEER 20 or more are now available, but at a substantial cost over the standard SEER 13 units.

f) Heating system efficiency.

ENERGY STAR qualified furnaces have annual fuel utilization efficiency (AFUE) ratings of 85% (oil) and 90% (natural gas), or greater, making them up to 15% more efficient than standard models. ENERGY STAR qualified boilers have annual fuel utilization efficiency (AFUE) ratings of 85% or greater. AFUE is the measure of heating equipment efficiency. They achieve greater efficiency with features, including: electronic ignition, eliminating the need to have the pilot light burning all the time, new combustion technologies that extract more heat from the same amount of fuel, and sealed combustion that uses outside air to fuel the burner, reducing drafts and improving safety.

g) Lighting power density (LPD).

Lighting demand accounts for 7% of residential building energy use and 17% of commercial energy use. New lighting technology can reduce this energy use by 50% to 75%. Light-emitting diode (LED), compact fluorescent (CFL), and halogen incandescent are three new lighting efficiency technologies that can replace incandescent (which wastes 90% of energy input as heat). LED and CFL lighting uses 75% less electricity to produce the same lighting level compared with incandescent, while halogen incandescent lighting uses 25% less electricity. They also have longer life. In a high-intensity discharge lighting system, higher efficiency bulbs should always be used. For example, high-intensity discharge white light lamp efficiencies from the highest to the lowest are as follows: metal halide pulse start ceramic, metal halide pulse start quartz, metal halide standard, and mercury vapor. When comparing lamp efficacy, those with higher lumen output per watt input should be selected. However, those lamps with high intensity can cause glare problems. Balancing of lamp efficacy and lighting quality must be considered. For visual comfort, lamps with a color rendering index of more than 80% is recommended. Lamps with correlated color temperature 3500 K soft white are recommended for office buildings, and 4100 K cool white for production areas. Reducing lighting power density also means reducing the heat produced from the lighting system, which will result in a lower cooling load in summer but a higher heating load in winter.

h) Energy efficiency appliances.

The U.S. Congress established minimum energy efficiency standards for many major appliances that manufacturers must follow. Inefficient appliances are gradually being phased out from the market. The standards are also periodically reviewed and revised by the U.S. DOE. Appliances with ENERGY STAR labels usually meet or exceed strict energy efficiency criteria established by the U.S. DOE and the U.S. EPA. List of ENERGY STAR–labeled appliances are as follows:

Commercial appliances
- Commercial clothes washers
- Vending machines
- Water coolers

Commercial food service equipment
- Commercial kitchen package
- Commercial dishwashers
- Commercial fryers
- Commercial griddles
- Commercial hot food holding cabinets
- Commercial ice machines
- Commercial ovens
- Commercial refrigerators & freezers
- Commercial steam cookers

Computers & electronics
- Audio/video
- Battery chargers
- Computers
- Displays
- Enterprise servers
- Imaging equipment (copiers and fax machines, digital duplicators, printers, scanners, all-in-one devices, and mailing machines)
- Televisions

ENERGY STAR-labeled appliances usually cost the same as nonlabeled appliances. They typically consume 40%-60% less energy by efficient design that also makes the appliances last longer and reduces heat production consequently lowering internal cooling load. Low-power sleep mode for inactive equipment is another important feature in these appliances. Although each appliance might consume small amounts of energy, their aggregate sum is high. Living standard and technology improvement resulted in the buying and use of more appliances. Future appliance standards could eliminate the energy-use growth in this sector significantly (EIA, 2011a).

In commercial buildings, office equipment and miscellaneous plug load can account for up to 25% of energy use (EIA, 2006). They are also a major source of internal heat gain. Reducing electricity used in this section will also decrease cooling loads but increase heating loads. Strategies to reduce electricity consumption from plug load involved shifting from desktop computers to laptop computers, using ENERGY STAR-labeled appliances, and using timer control for some equipment, such as coffee makers, computer monitors, and water coolers. Laptop computers are designed to save energy so they can depend on their batteries. Therefore, they use the most energy efficient hard disks, CPUs, displays (LCD), and adapters that are available. The savings could be more than 50% compared with conventional desktop computers and their screens. Studies for 50% Advanced Energy Design Guides for office buildings showed that 3-4 W/m^2 plug load could be reduced using the mentioned strategies (National Renewable Energy Laboratory [NREL], 2010; U.S. DOE, 2010b).

2.3.3 Building management.

i) Thermostat setting.

The U.S. DOE recommends setting thermostats to 20°C (68°F) in winter and 12°C-15°C (53°F-58°F) when there are no occupants or when building occupants are asleep. Even though heating systems work harder to bring the temperature back to the setting point, the rate of heat loss to the outside atmosphere is reduced by decreasing temperature differences during the setback period resulting in more energy savings. By turning the thermostat back 5°C-7°C (10°F-15°F) for 8 hours, heating load can be reduced by about 5% to 15% a year (DOE Energy Efficiency & Renewable Energy, 2012). The percentage of savings from setback is greater for buildings in milder climates than for those in more severe climates. In the summer, the recommendation is setting the thermostat to 26°C (78°F) and elevating it when there is no need for cooling (this can be done manually or by using programmable thermostat). However, programmable thermostats are generally not recommended for heat pump systems that are capable of operating in both cooling and heating modes because in heating mode, setting back the thermostat temperature will make the unit operate inefficiently.

Setback temperatures during heating season when buildings are unoccupied can be allowed to reach as low as 7°C (45°F). In cooling season, the setback temperature can be allowed to reach as high as 32°C (90°F). Thermostats should be capable of adjusting to 13°C (55°F) or lower for heating systems and up to 29°C (85°F) or higher for cooling systems. However, indoor temperatures could not immediately return to the daytime setpoint. Therefore, enough time should be allowed for the temperature to decrease or increase to the setpoints before buildings are opened in the morning. Failure to do so will lead to increasing unmet load hours. With systems that can operate in both cooling and heating modes, thermostats should be capable of providing a temperature range above or below the temperature setting point (deadband) of 3°C (5°F) or more (ASHRAE, 2006a).

j) Cold deck reset.

Cooling coils are cooling the supply air temperature at 12.2°C (55°F) so that the temperature in the occupancy zone on the hottest day could be maintained at comfort conditions. During other periods when the outside temperature is mild, the supply temperature can be set higher. For example, at 26.7°C (80°F) outside temperature, the supply air temperature is set to 12.8°C (54°F); at 15.6°C (60°F) outside temperature the supply air temperature is set at 16.1°C (61°F), and then the supply air temperature is set proportionally between the two points. Buildings with high internal loads might need to set this value lower, or buildings with high efficiency lighting systems that have low internal loads might need to set this value lower than normal buildings.

2.3.4 Combined strategies.

k) Passive house.

A passive house is a building that can maintain its indoor comfort level without active heating and cooling systems (Passive House Institute, 2012). The passive house (or Passivhaus in German) standard originated from the Institute for Housing and the Environment in Germany. It was developed in cold climates with results in energy saving up to 90% compared with conventional central European buildings, and more than 75% compared with average new buildings. Passive house principles make use of supply air heating in an extremely well insulated building. The heating load of less than 10 W/m^2 makes certain that the required heat can be met by heated supply air. The standard requirements are:

- Passive houses require less than 15 $kWh/m^2 \cdot y$ (4746 $Btu/ft^2 \cdot y$) for heating or cooling (relating to the living space) as calculated with the Passivhaus Planning Package,
- The heating/cooling load is limited to a maximum of 10 W/m^2,
- Total primary energy consumption may not exceed 120 kWh/m^2,
- Passive houses must be airtight with air infiltration no more than 0.6 house volume/h at 50 Pa ($n_{50} \leq 0.6/h$), and
- In warmer climates or during summer months, excessive temperatures may not occur more than 10% of the time.

In addition, the following standards are recommended, varying with climate(Passive House Institute U.S., 2012):

- Window U-factor ≤ 0.8 W/m^2K,
- Ventilation system with heat recovery with ≥ 75% efficiency with low electric consumption @ 0.45 Wh/m^3, and
- Thermal Bridge Free Construction ≤ 0.01 W/mK.

l) Net zero energy building (ZEB).

A net Zero Energy Building (ZEB) is a building that over the course of a year does not use more energy than it generates (Torcellini, Pless, Deru, & Crawley, 2006). This can be achieved by significantly reducing energy demands so that the energy needs can be met by on-site renewable energy. Designing with ZEB often makes use of passive solar, prevailing ventilation, and daylighting and is used together with high performance building design strategies such as super envelope, high efficiency glazing, high performance HVAC systems, rooftop grid-connected PV systems, and solar hot water systems. Achieving ZEBs without the electric grid is difficult. A stand-alone ZEB needs oversized renewable energy systems and a backup generator from other energy sources such as propane. These problems are eliminated in a grid-connected system. The U.S. DOE has a goal for facilitating marketable ZEBs by 2025.

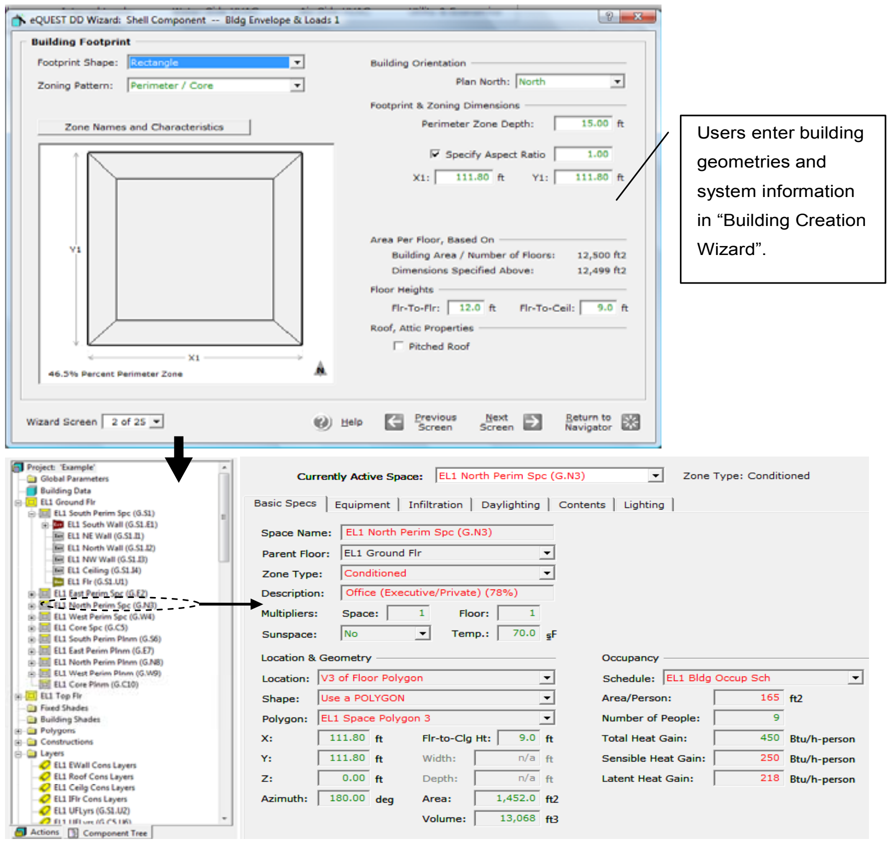
2.4 Building Stock Modeling

In this study, energy efficiency design options were investigated together with grid-connected PV system performance installed on the building. Existing building stock energy use patterns and consumption were first modeled and simulated so that they could be used for benchmarking. Requirements for benchmark models are available from Building America for residential buildings and DOE reference commercial buildings for commercial buildings (formerly known as commercial building benchmark models). Then these buildings were made compliant with ASHRAE 90.1-2007 and 90.2-2007 standards. The simulation procedures followed Section 8.7 Prescriptive Design in ASHRAE 90.2-2007 for residential building and Appendix G Performance Rating Method in ASHRAE 90.1-2007 for commercial and industrial buildings. The following sections detail software capabilities, demonstrate steps and variables used in modeling, as well as results from the simulations.

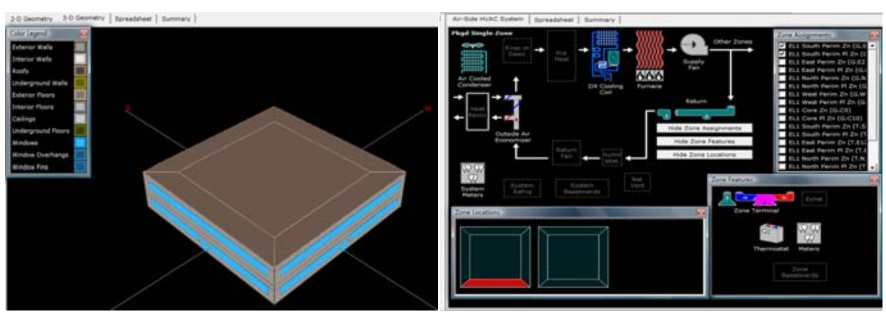
2.4.1 Building energy simulation software.

eQUEST® building simulation software was used in this study to simulate hourly energy demand. eQUEST® is a whole-building energy analysis software that uses the latest version of DOE-2 as a simulation engine. The DOE-2 building energy simulation and cost calculation program was initially released by the Lawrence Berkeley National Laboratory (LBNL) in 1978. The program has been updated continuously by LBNL in collaboration with James J. Hirsch and Associates, mostly under funding from the U.S. DOE until version 2.1E in 2003. Since then, James J. Hirsch and Associates has been continuing the development of DOE-2; the latest version is DOE-2.2. In DOE-2, the transient heat transfer calculation methods are used to simulate the dynamic heat transfer through building envelopes. From the literature, results from DOE-2 simulations were shown to vary from 10% to 26% from measured data (Haberl & Cho, 2004). eQUEST was tested in accordance to ANSI/ASHRAE Standard 140-2007 Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs, and it is qualified for use to evaluate building energy performance for government subsidy programs and building rating systems (U.S. DOE, 2012a). It also meets all requirements for energy simulation software indicated in ASHRAE 90.1 Appendix G Performance Rating Method’s guidelines for acceptable energy simulation software mentioned in section 2.2.4. eQUEST® is available for free from http://doe2.com/eQUEST/ (DOE2.com, 2012).

Within eQUEST® graphic user interface, DOE-2.2 performs an hourly simulation of input buildings for 8,760 hours or one full year. It calculates hourly cooling load, heating load, and other energy loads such as lighting, domestic hot water, or other equipment. Users can model their buildings using “Building Creation Wizard” which quickly generates detailed building input files from simple building envelope and systems input.



Wizard creates detail building inputs from user inputs. Many inputs are by default based on typical values, codes and standards and can be edited.



Building geometries and system diagrams are shown and can be interactively edited.

Figure 24. eQUEST Software can quickly generate a detailed input file from user building information input using default values based on typical values, codes, and standards that can be interactively edited later.

2.4.2 Baseline existing buildings modeling.

Various sources were used in the development of baseline building models. The national energy consumption surveys conducted by EIA were used to provide building stock characteristics such as building areas, number of stories, construction types, occupancy numbers, building systems, and average energy consumption. Buildings are divided into 3 types: residential, commercial, and industrial buildings. These baseline buildings represent typical building construction and use patterns at a fixed point in time. They were used as a benchmark to track energy reduction and energy efficiency design strategy options.

The simulation took into account the impact of local weather. Building models were simulated in all U.S. climate zones. According to ASHRAE, there are 8 climate zones in the U.S. Some of these climate zones can be divided further into different divisions which are marine, moist, and dry. Sixteen cities representing each subdivision within each climate zone were previously selected in the commercial reference buildings research project (Michael Deru, 2011). These cities were then used as reference cities in other studies such as the technical support studies for ASHRAE's Advance Energy Design Guide (AEDG). This dissertation also used these 16 cities as reference cities for the simulations. The locations of each city – except Fairbanks – are shown in Figure 25 and their weather characteristics are shown in Table 2. Climate types vary from hot to warm, mixed, cool, cold, and very cold, representing a wide range of conditions that challenge architects to design energy efficient buildings suitable for each climate type. The weather data files used in the simulations were Typical Meteorological Year Version 3 (TMY3) available from the National Solar Radiation Data Base (NSRDB).

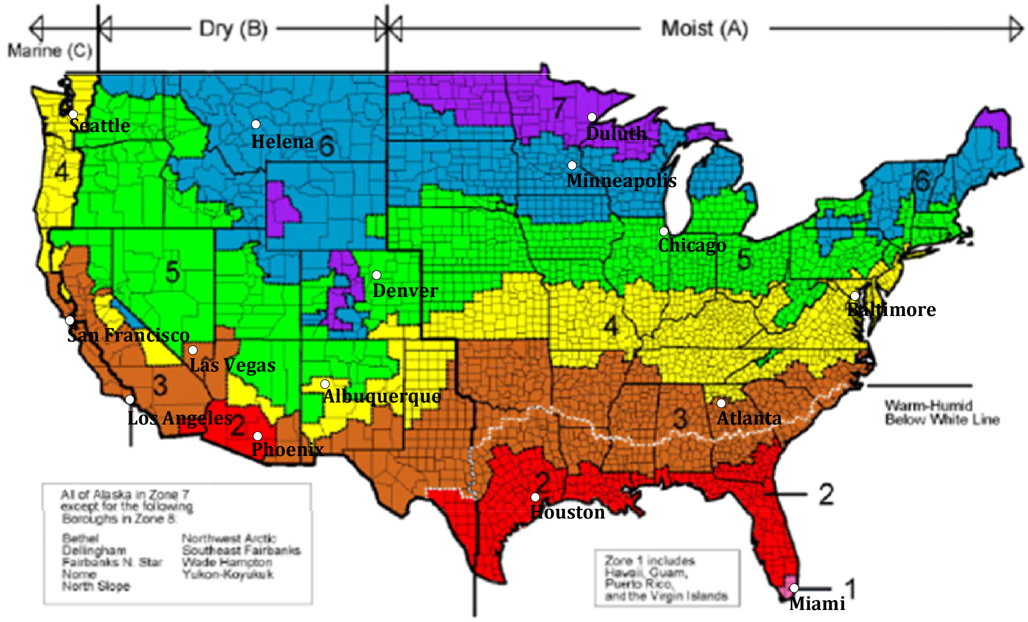


Figure 25. Locations of representative cities.

Table 2. Representative cities and their climate characteristics.

Location	zone	Description	Degree days (°C)	Average annual temperature (°C)	Average daily temperature swing (°C)
Miami	1A	Very hot – Humid	5000 < CDD10°C	25.6	6.7
Houston	2A	Hot – Humid	3500 < CDD10°C ≤ 5000	20.6	11.1
Phoenix	2B	Hot – Dry	3500 < CDD10°C ≤ 5000	20.6	14.4
Atlanta	3A	Warm – Humid	2500 < CDD10°C ≤ 3500	16.7	10.6
Los Angeles	3B	Warm – Dry	2500 < CDD10°C ≤ 3500	16.7	7.2
Las Vegas	3B	Warm – Dry	2500 < CDD10°C ≤ 3500	16.7	13
San Francisco	3C	Warm – Marine	HDD18°C ≤ 2000	15.6	6.7
Baltimore	4A	Mixed – Humid	CDD10°C ≤ 2500 AND HDD18°C ≤ 3000	12.8	10.6
Albuquerque	4B	Mixed – Dry	CDD10°C ≤ 2500 AND HDD18°C ≤ 3000	12.8	14.4
Seattle	4C	Mixed – Marine	2000 < HDD18°C ≤ 3000	12.8	7.8
Chicago	5A	Cool – Humid	3000 < HDD18°C ≤ 4000	9.4	10
Denver	5B	Cool – Dry	3000 < HDD18°C ≤ 4000	9.4	14.4
Minneapolis	6A	Cold – Humid	4000 < HDD18°C ≤ 5000	6.7	10
Helena	6B	Cold – Dry	4000 < HDD18°C ≤ 5000	6.7	12.5
Duluth	7	Very Cold	5000 < HDD18°C ≤ 7000	3.3	9.5
Fairbanks	8	Subarctic	7000 < HDD18°C	-4.4	9.5

Normal and 24-hour schedules available in eQUEST software for each building type were used. The program automatically generated occupancy characteristics based on the building and schedule types selected. The following occupancy characteristics are automatically determined: occupant loads, receptacle loads, water heating demand, installed lighting power, and outdoor air ventilation rate.

a) Residential buildings.

Results from the Residential Energy Consumption Survey (RECS) in 2005 showed that 65% of residential buildings are detached single-family units. Fifty-six percent have areas smaller than 150 m^2 (1,500 ft^2), another 25% have areas between 150 – 249 m^2 (1,500-2,499 ft^2). Forty-two percent are 1-story houses and 25% are 2-story houses. In the simulation, there were two types of residential building (Figure 26) based on RECS data as follows:

- Small: 1 story, 120 m^2 (1,200 ft^2)
- Medium: 2 stories, 240 m^2 (2,400 ft^2)

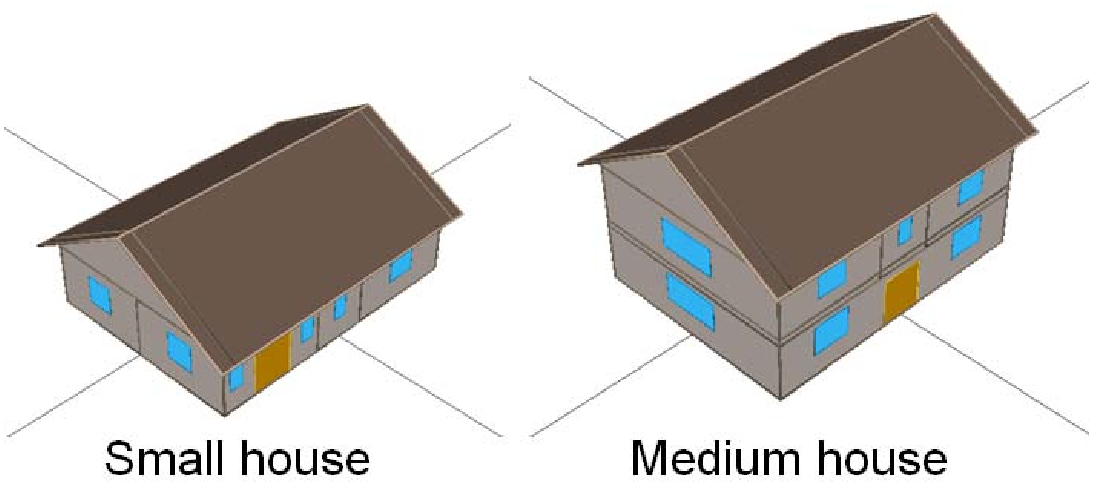


Figure 26. Residential building models in eQUEST.

House models have an aspect ratio of 1.33. Their dimensions are 10 m x 12 m. The floor-to-floor height is 2.7 m and the floor-to-ceiling height is 2.4 m. The roof is a 30° tilted, pitched roof with 0.60 m overhang.

To track energy saving when applying various design strategies, the U.S. DOE Residential Buildings Program and the NREL developed the Building America House Simulation Protocols (Robert Hendron & Cheryn Engebrecht, 2010) in consultation with the building industry teams. The benchmark selected for this study is generally consistent with mid-1990s standard practice. The protocol's requirements used in this study are summarized below:

- Default R-Values for 2" x 6" framed wall cavities insulation is 3.346 m^2K/W (19 $h \cdot ft^2 \cdot °F/Btu$).
- Default R-Values for cavities insulation in roofs is 3.346 m^2K/W (19 $h \cdot ft^2 \cdot °F/Btu$).
- Buildings in climate zone 1-3 have single clear vertical fenestration, and buildings in other climate zones have double pane windows.
- Window area is 15% of wall area in each direction.
- Default solar absorptivity is 0.60 for walls and 0.85 for medium colored shingles.
- The default AFUE is 67%. This value was calculated using equation (1).

  $$AFUE = (Base\ AFUE)x(1 - M)^{age} \quad (1)$$

  Gas furnace base AFUE is 78% with seldom maintenance factor of 0.015 and assumed 10 years in operation.
- The default SEER is 7.37. This value was calculated using equation (2).

  $$SEER = (Base\ SEER)x(1 - M)^{age} \quad (2)$$

  Split central air conditioner base SEER is 10 with seldom maintenance factor of 0.03 and assumed 10 years in operation.

- Thermostat setpoint: Heating 21.6°C (71°F) and cooling 24.4°C (76°F) with no set back period.
- The default gas water heater EF is 0.49. This value was calculated using equation (3).

$$EF = (Base\ EF)x(1 - M)^{age} \quad (3)$$

Gas water heater base EF is 0.54 with seldom maintenance factor of 0.01 and assumed 10 years in operation.

- End-use water temperature setpoint is 43.3°C (110°F).

In addition to Building America House Simulation Protocols, eQUEST default building use schedule for "residential, daytime unoccupied, typical use" was used in the simulation. There are two occupants in small houses and four occupants in medium houses.

Energy use intensity in a small house simulated in each climate zone is compared with national average energy use intensity from RECS and shown in Figure 27. Buildings in colder climates use more energy for space heating, which mostly depends on natural gas (Figure 28). The energy intensity use pattern is roughly consistent with the national averages shown in Figure 10 where more energy is used in buildings in the northern areas compared with southern areas.

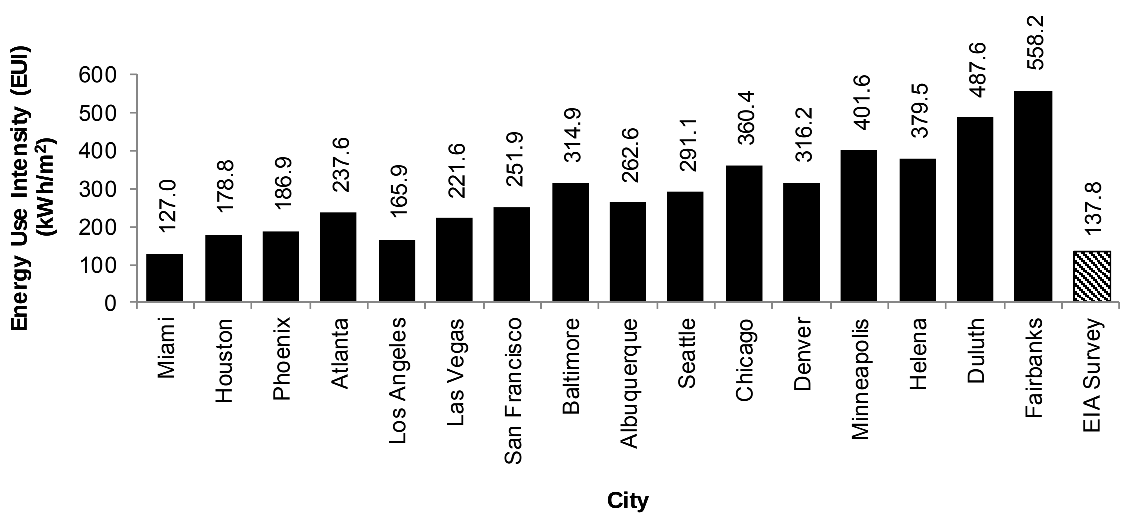


Figure 27. Simulated energy use intensity in residential buildings located in 16 cities compared with EIA residential building national average energy intensity.

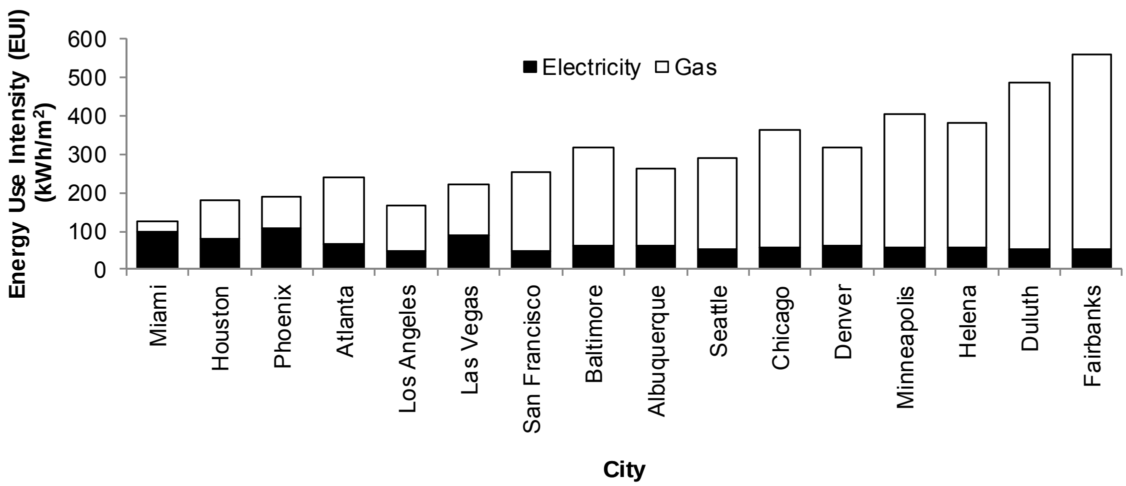


Figure 28. Simulated electricity and gas use intensity in residential buildings located in 16 cities.

b) Commercial buildings.

Although no single commercial building type dominates the commercial buildings sector, office buildings are the most common and account for more than 800,000 buildings or 17% of total commercial buildings. Office buildings comprised more than 12 billion square feet of floor space, the most of any building type. For consistency and ability to compare between studies, office building geometries, size, and some characteristics used in commercial reference buildings program (B. Griffith et al., 2008; Torcellini, Deru, Griffith, & Benne, 2008) were used in this study whenever possible. Some detailed input available from commercial reference buildings project could not be used in this study because the simulation software used in the commercial reference building was EnergyPlus. It was not possible to make a model with exactly the same input using two different energy simulation tools.

DOE's Commercial reference buildings models are also based on data from CBECS with some modifications. The three types of commercial building models (Figure 29) are as follows:

- Small office building: 1 story, 500 m^2 (5,000 ft^2).

- Medium office building: 3 stories, 5,363 m^2 (53,630 ft^2) with ground parking.
- Big office building: 12 stories and 1 basement, 46,024 m^2 (460,240 ft^2) with a parking structure.

All commercial building aspect ratios are 1.5. The small office building's foot print is 18 m x 28 m. It has a 15° tilted roof. The medium office building's foot print is 33.5 m x 49.5 m. and it has a flat roof. The big office building's foot print is 50 m x 70 m and it has a flat roof. All buildings floor-to-floor height is 3.9 m and floor-to-ceiling height is 2.7 m. Window area is 40% of wall area in each direction without shading.

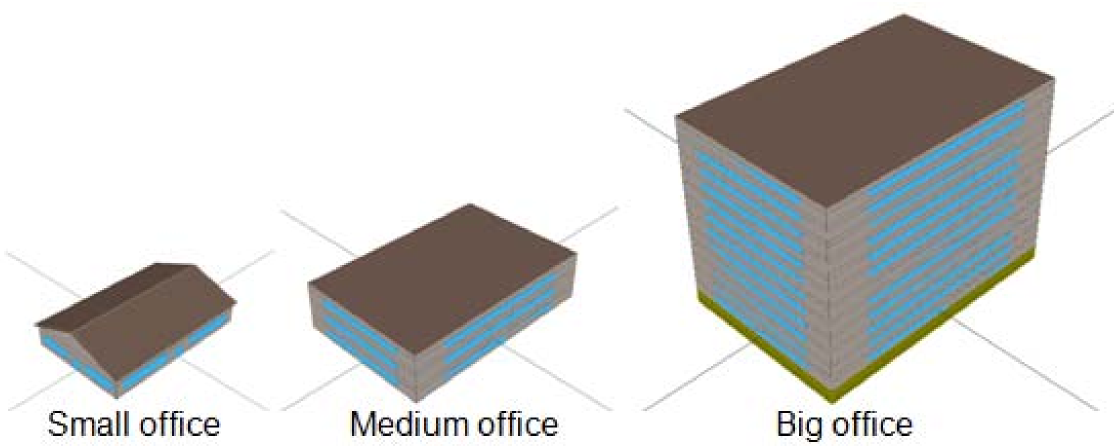


Figure 29. Office building models in eQUEST.

In this study, a set of standard practices represented in existing buildings built after 1980 were used. Their inputs are summarized below and in Table 3:

- Small commercial building: Package rooftop air conditioner, direct expansion coil and fossil fuel furnace, COP 3.07, EF 0.80.
- Medium commercial building: Package rooftop VAV with reheat, direct expansion coil with hot-water fossil fuel boiler, COP 2.8, EF 0.80.

- Big commercial building: Package rooftop VAV with reheat, chiller water system with hot-water fossil fuel boiler, COP 5.2, EF 0.70.
- Service hot water system efficiency is 0.78.

Table 3. Envelope characteristics of existing commercial buildings.

City	Roof U (W/m^2K)	Wall U (W/m^2K)	Fenestration U (W/m^2K)	Fenestration SHGC
Miami	0.42	3.13	1.028	0.25
Houston	0.38	0.85	1.028	0.25
Phoenix	0.26	1.36	1.028	0.25
Atlanta	0.41	0.74	0.721	0.25
Los Angeles	0.57	1.25	1.028	0.26
Las Vegas	0.27	0.91	1.028	0.44
San Francisco	0.50	0.74	0.721	0.25
Baltimore	0.33	0.51	0.591	0.39
Albuquerque	0.34	0.57	0.721	0.36
Seattle	0.36	0.52	0.721	0.36
Chicago	0.30	0.47	0.591	0.39
Denver	0.29	0.47	0.591	0.39
Minneapolis	0.25	0.37	0.521	0.39
Helena	0.27	0.41	0.521	0.39
Duluth	0.23	0.33	0.521	0.49
Fairbanks	0.17	0.26	0.521	0.62

Simulated energy use intensity in medium office buildings located in 16 cities is shown in Figure 30. Comparing with the energy intensity output from medium reference office buildings published by DOE commercial reference building, the output from this study is lower than the reference buildings by 1% to

15%. The majority of energy used in office buildings is electricity, except for buildings in very cold climates such as Minneapolis, Duluth, and Fairbanks (Figure 31). This is due to the commercial building internal load, which is more dominant than the load from building envelope.

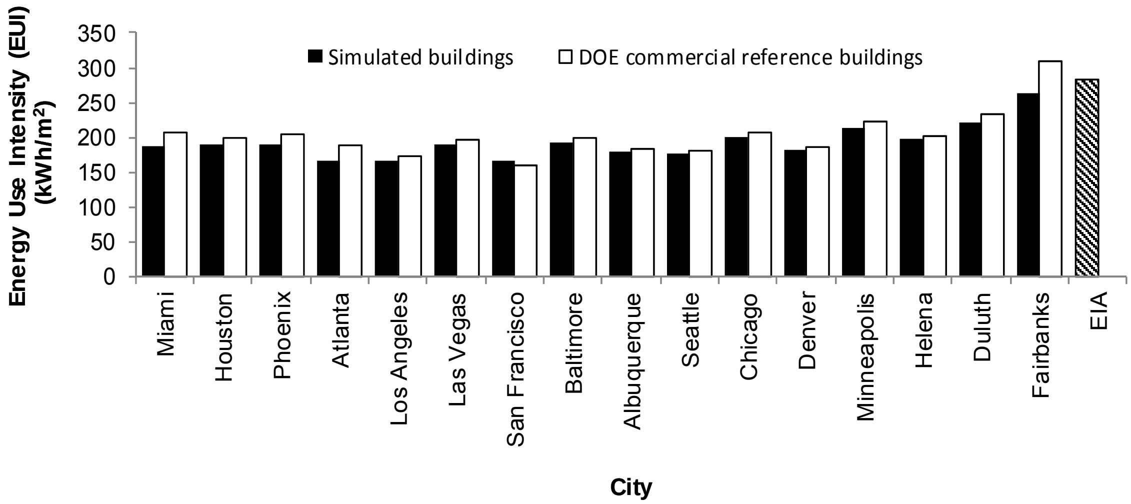


Figure 30. Energy use intensity in commercial buildings located in 16 cities compared with EIA national average energy intensity in commercial buildings.

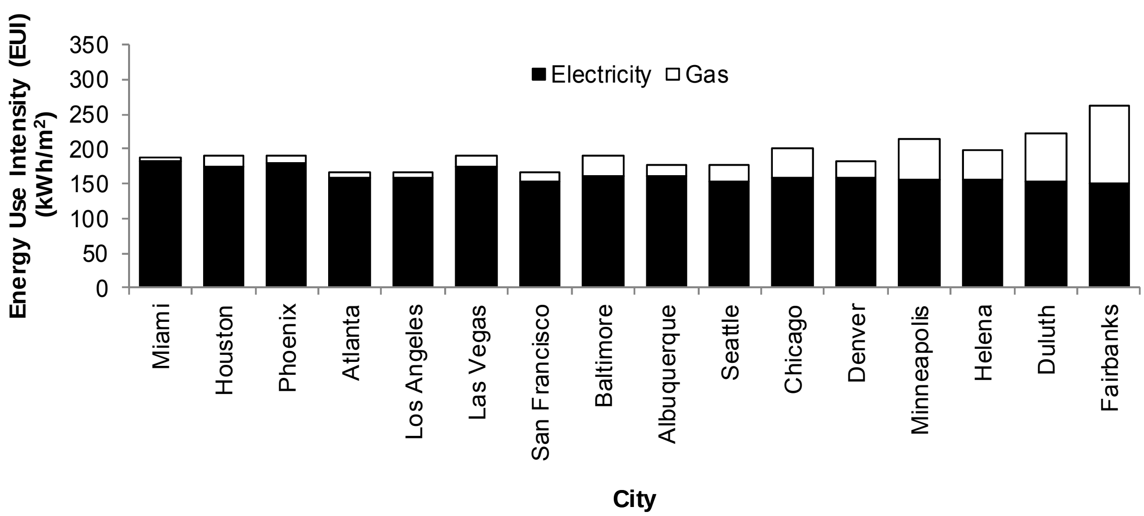


Figure 31. Electricity and gas use intensity in simulated commercial buildings located in 16 cities.

c) Industrial buildings.

From MECS, the average area of industrial building is 8,000 m^2 (80,000 ft^2). There is no guideline in modeling this type of building. Therefore, most of the model characteristics used were that of medium commercial buildings (Figure 32). In this simulation, the process load was excluded because of the lack of information. Output energy uses are loads from the cooling system, heating system, lighting system, general appliances, and hot water service system.

- Typical: 1 story, 10,000 m^2 (100,000 ft^2) with ground parking.

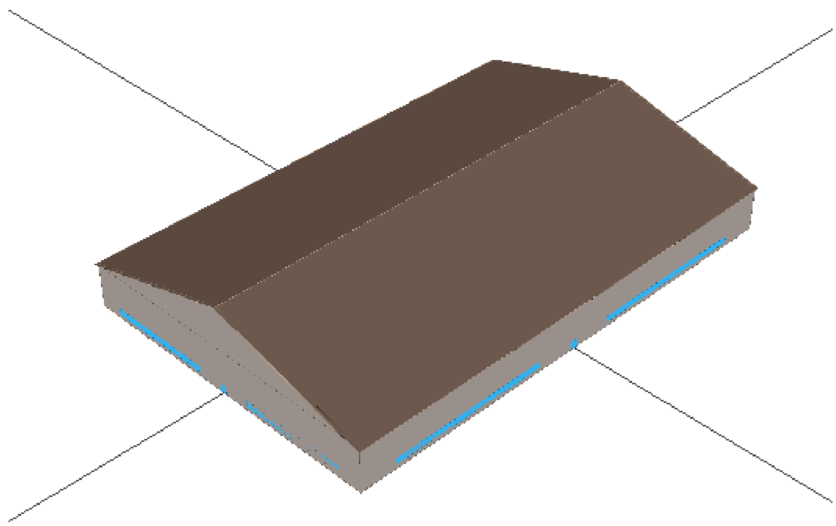


Figure 32. An industrial building model in eQUEST.

The industrial building's aspect ratio is 1.5, its footprint is 80 m x 125 m, it has a 15° tilted roof, and the building floor to ceiling height is 10.5 m.

Simulated energy use intensity in industrial buildings located in 16 cities are shown in Figure 33. Industrial buildings use a similar proportion of electricity to natural gas used by commercial buildings even though they have different geometry; however, higher outside envelope proportions result in higher proportional use of natural gas (Figure 34).

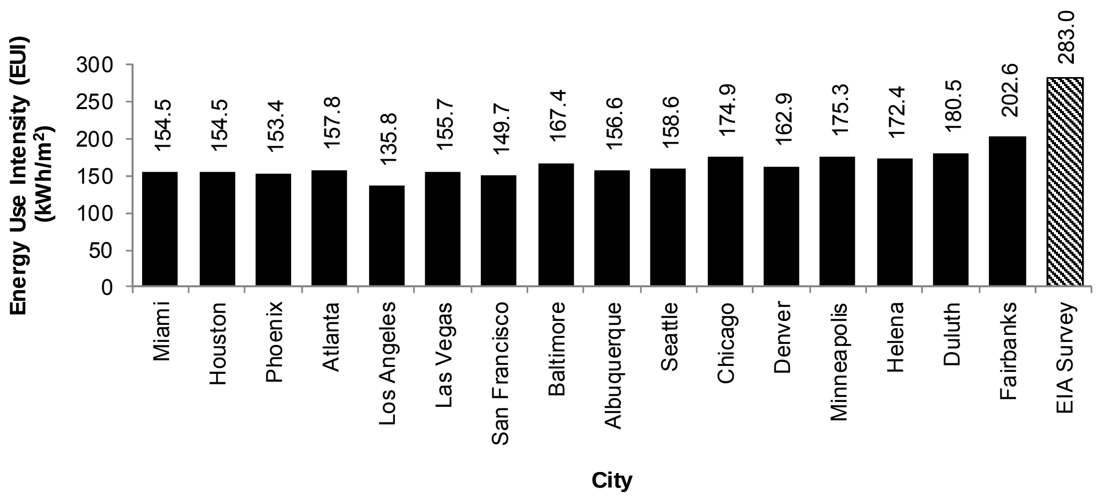


Figure 33. Energy use intensity in industrial buildings located in 16 cities compared with EIA national average energy intensity in industrial buildings.

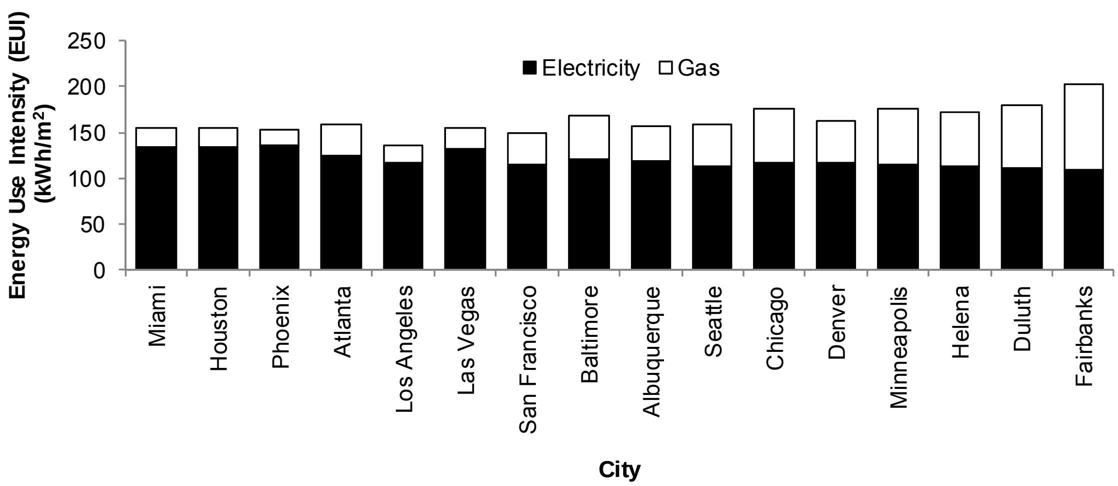


Figure 34. Electricity and gas use intensity in industrial buildings located in 16 cities.

d) Building energy use characteristics from simulations.

Residential buildings' annual energy consumption from simulations vary from climate to climate. Except for Miami, the largest portion of energy use is for space heating (Figure 35). For electricity use, building equipment including lighting systems has the largest consumption. The net cooling load is due to heat gains, of which the largest component is solar gain from the envelope followed by internal gains from the occupants, equipment and lighting systems, and infiltration. With careful design in hot regions, free cooling through the building foundation can be obtained. The net residential heating load is due to heat losses through ventilation, infiltration, and envelope minus internal gain from occupants, equipment, and lighting systems as well as solar gain through windows.

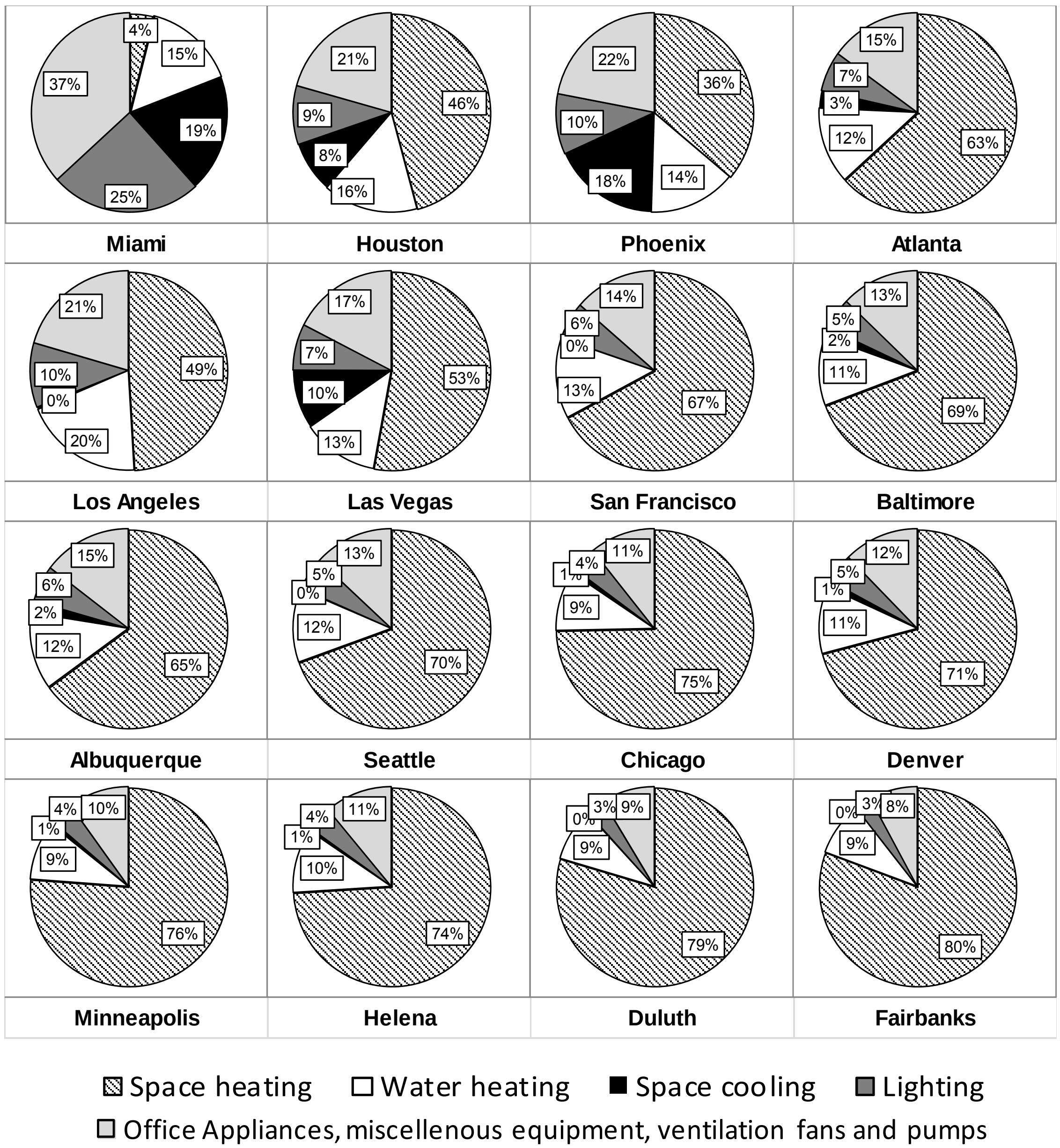


Figure 35. Small house energy consumption proportion in 16 cities.

In commercial buildings, internal loads, which are office appliances, miscellaneous equipment, ventilation fans, pumps and lighting systems, have the highest portion of energy use, except in very cold climates where heating systems are consuming slightly more energy than internal loads.

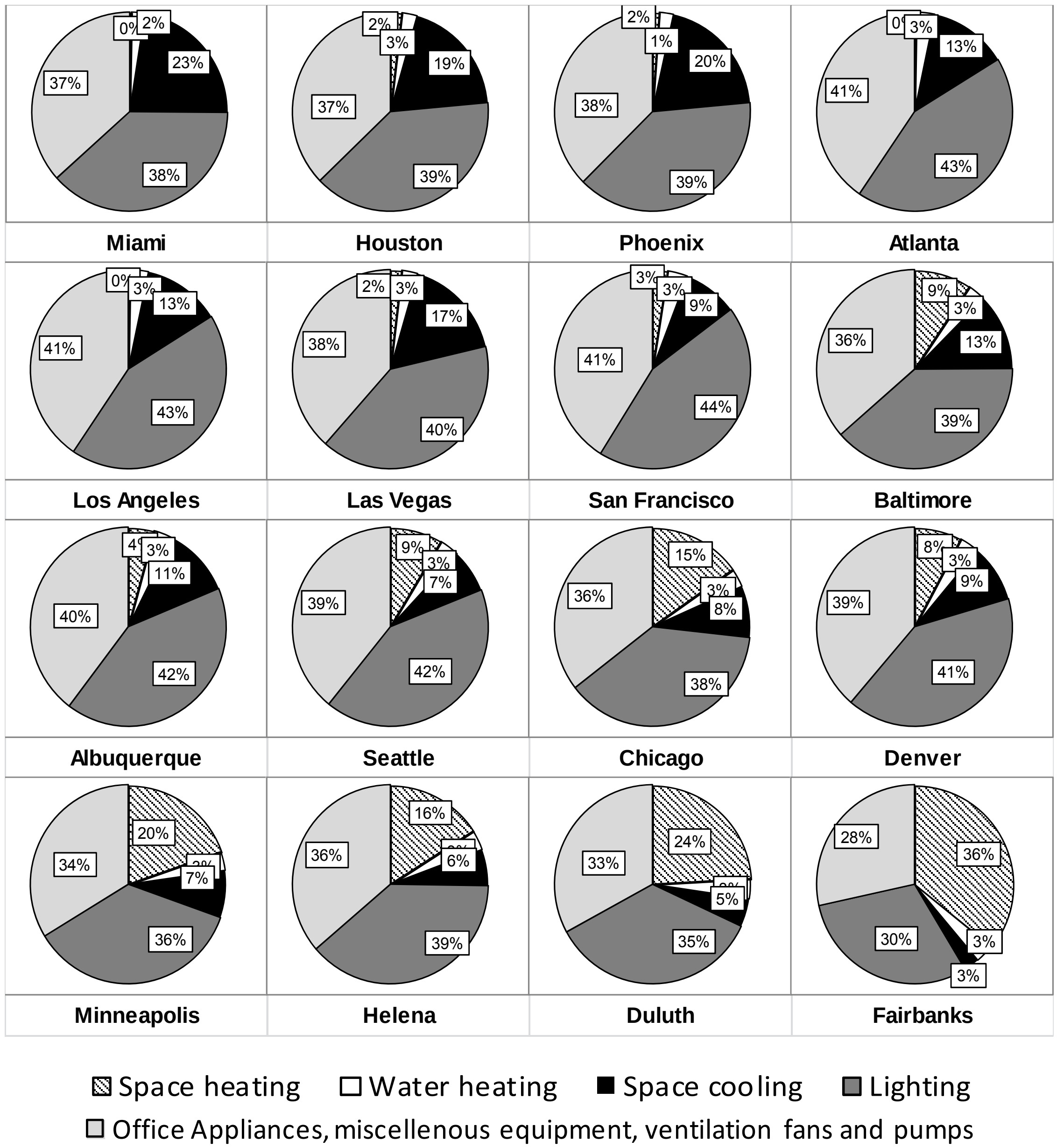


Figure 36. Medium office building energy consumption proportion in 16 cities.

Excluding process load, lighting becomes the highest energy consumer in industrial buildings. Artificial light is needed for internal space because of their primary shape (high and deep). Heat gain through the building is small with low envelope to volume ratio.

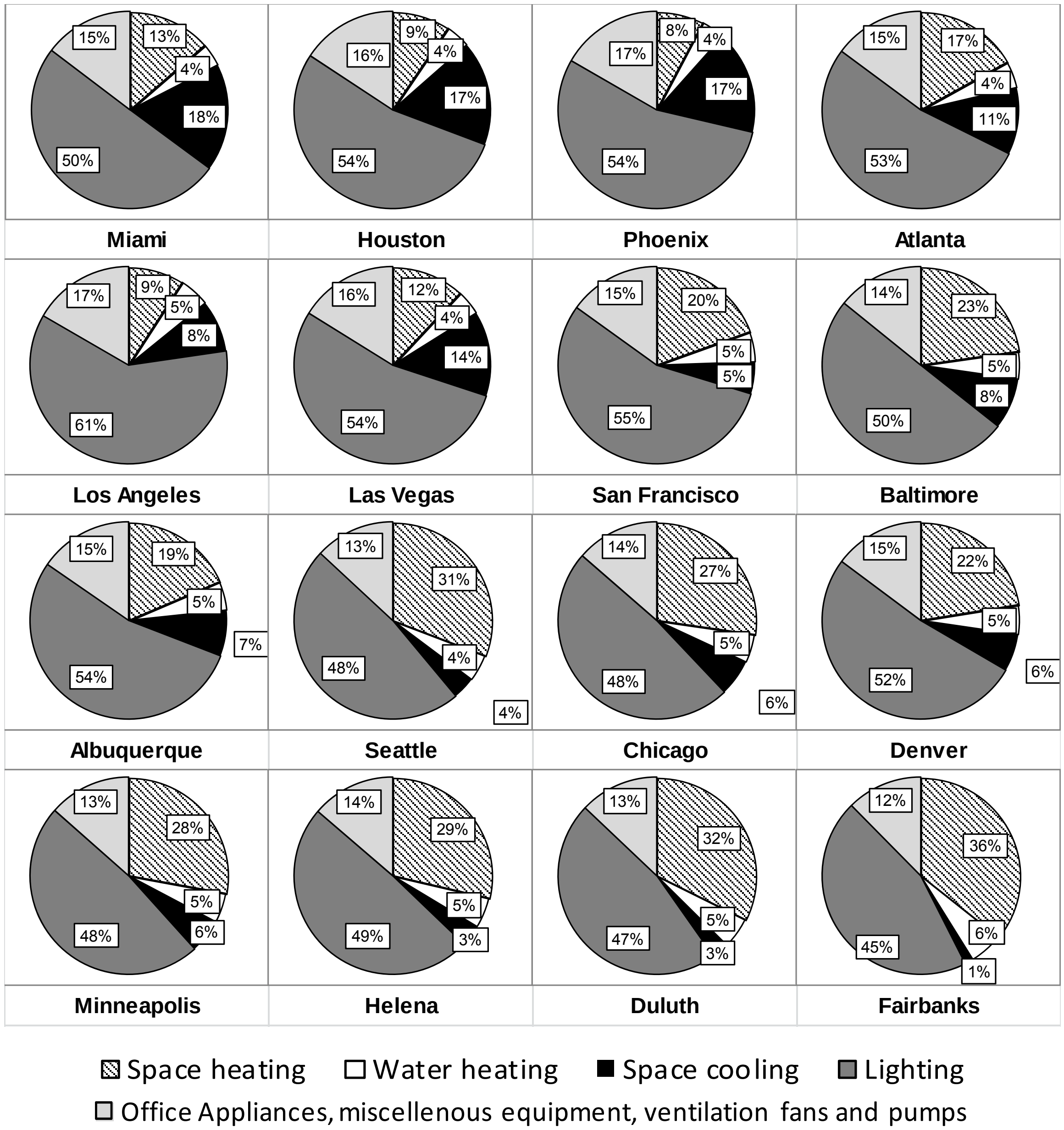


Figure 37. Industrial building energy consumption proportion in 16 cities.

2.4.3 Baseline buildings modeling compliance with ASHRAE standards.

ASHRAE 90.2-2007 was used as a guideline for code compliant residential modeling, while ASHRAE 90.1-2007 was used as a guideline for code compliant commercial and industrial buildings.

a) ASHRAE 90.2-2007 compliance: Residential buildings.

Modeling baseline residential building compliance with ASHRAE 90.2-2007 is specified in ASHRAE 90.2-2007, Section 8.7 Prescriptive Design, within Section 8 Annual Energy Cost Method. The prescriptive baseline model must meet the requirements of building envelope, HVAC system and equipment, and service water heating specified in ASHRAE 90.2-2007 Sections 5, 6, and 7. Sets of minimum requirements for performance path building envelope criteria are shown in Table 4. Other requirements that are applicable to residential models used in this study are summarized below:

- The exposed ceiling area is assumed to be a horizontal, unventilated, light-weight construction meeting the U-factor requirements for ceilings with attics.
- One-fourth of each wall type and fenestration area must face each cardinal orientation.
- The building must have one 40 ft^2 opaque wood door facing north for each living unit. No U-factor requirement for wood doors.
- No perimeter insulation requirement for slab-on-grade envelope.
- No self or external shading.
- Exterior absorptivity is 0.5 for all exterior wall and 0.2 for all for roof regardless of color.
- Assumed internal shadings that reduce glass shading coefficient (SC) by 30%.
- Thermostat setpoint:
    - Heating unoccupied/ occupied 15.6°C/20.0°C (60°F/68°F).
    - Cooling unoccupied/ occupied 29.4°C/25.6°C (85°F/78°F).
- Hot water consumption 16.45 gal/person/day (with clothes washer and a spa tub in the unit).

Table 4. ASHRAE 90.2-2007 envelope requirements.

City	Roof Attic Space-Wood-Cavity	Wall Above-Grade Frame-Wood	Fenestration	
	U (W/m^{2}K)	U (W/m^{2}K)	U (W/m^{2}K)	SHGC
Miami	0.20	0.51	3.80	0.37
Houston	0.20	0.47	3.80	0.37
Phoenix	0.20	0.47	3.80	0.37
Atlanta	0.20	0.47	2.67	0.40
Los Angeles	0.20	0.47	2.67	0.40
Las Vegas	0.20	0.47	2.67	0.40
San Francisco	0.20	0.47	2.67	0.40
Baltimore	0.15	0.33	1.99	NR
Albuquerque	0.15	0.33	1.99	NR
Seattle	0.15	0.33	1.99	NR
Chicago	0.13	0.33	1.99	NR
Denver	0.13	0.33	1.99	NR
Minneapolis	0.12	0.25	1.99	NR
Helena	0.12	0.25	1.99	NR
Duluth	0.12	0.20	1.99	NR
Fairbanks	0.11	0.20	1.99	NR

NR = Not required
All U-factors are air-to-air including interior and exterior air films

Details input in eQUEST® are shown in Appendix A in IP unit.

b) ASHRAE 90.1-2007 compliance: Commercial and industrial buildings.

Modeling baseline building compliance with ASHRAE 90.1-2007 is specified in ASHRAE 90.1-2007 Appendix G Performance Rating Method. The procedures in Appendix G are intended for modeling a baseline building that can be used for benchmarking the energy efficiency of building design that exceeds the requirement of the ASHRAE 90.1 standard. All requirements in ASHRAE 90.1-2007 Sections 5.4, 6.4, 7.4, 8.4, 9.4, and 10.4 must be met. Sets of minimum requirements for performance path building envelope criteria are shown in Table 5 together with high-limit shut off for economizer in each climate zone. Other requirements for modeling baseline buildings are summarized as follows:

- Interior lighting power allowances follow space-by-space method in ASHRAE 90.1-2007, Table 9.6.1, and no automatic lighting control.
- Baseline HVAC types and descriptions were modeled according to ASHRAE 90.1-2007, Table G3.1.1A, and Table G3.1.1B.

  Small commercial buildings: Package rooftop AC.
  - Constant fan
  - Direct expansion cooling
  - Fossil fuel furnace

  Medium commercial buildings and industrial buildings: Package rooftop VAV with reheat.
  - VAV fan
  - Direct expansion cooling
  - Hot-water fossil fuel boiler

  Big commercial buildings: Package rooftop VAV with reheat.
  - VAV fan
  - Chilled water cooling
  - Hot-water fossil fuel boiler
- HVAC equipment capacities must be based on sizing run for each orientation and must be oversized by 15% for cooling and 25% for heating. The weather condition used for sizing runs must be based on historical weather files that provide peak conditions of design days developed using 99.6% heating design temperatures and 1% dry-bulb and 1% wet-bulb cooling design temperatures.
- HVAC minimum equipment efficiencies requirement followed ASHRAE 90.1-2007, Tables 6.8.1A through 6.8.1G.
- Use actual or typical building schedules to model hourly variation of occupancy, lighting power, equipment power, thermostat setpoints and HVAC system operation.

- All roof surface reflectance is 0.30.
- Vertical fenestrations are less than 40% of total above-grade wall area and have no exterior shading.

Table 5. ASHRAE 90.1-2007 envelope and economizer requirements.

City	Insulation entirely above deck roof U (W/m^2K)	Steel framed wall U (W/m^2K)	Below grade wall U (W/m^2K)	Steel joist floor U (W/m^2K	Fenestration U (W/m^2K)	Fenestration SHGC	Economizer high limit (°C)
Miami	0.360	0.705	6.473	1.986	6.81	0.25	NR
Houston	0.273	0.705	6.473	0.296	4.26	0.25	NR
Phoenix	0.273	0.705	6.473	0.296	4.26	0.25	NR
Atlanta	0.273	0.479	6.473	0.296	3.69	0.25	NR
Los Angeles	0.273	0.479	6.473	0.296	3.69	0.25	23.9
Las Vegas	0.273	0.479	6.473	0.296	3.69	0.25	23.9
San Francisco	0.273	0.479	6.473	0.296	3.69	0.25	23.9
Baltimore	0.273	0.365	6.473	0.214	3.12	0.40	NR
Albuquerque	0.273	0.365	6.473	0.214	3.12	0.40	23.9
Seattle	0.273	0.365	6.473	0.214	3.12	0.40	23.9
Chicago	0.273	0.365	0.678	0.214	3.12	0.40	21.1
Denver	0.273	0.365	0.678	0.214	3.12	0.40	23.9
Minneapolis	0.273	0.365	0.678	0.214	2.56	0.40	21.1
Helena	0.273	0.365	0.678	0.214	2.56	0.40	23.9
Duluth	0.273	0.365	0.678	0.214	2.56	0.45	21.1
Fairbanks	0.273	0.365	0.678	0.183	2.56	0.45	23.9

NR = Not required
Simulation results must show unmet load hours less than 300.

Details input in eQUEST are shown in Appendix A in IP unit.

c) Results.

Annual energy consumption in ASHRAE compliant buildings: In this study, ASHRAE standards were found to be able to reduce energy consumption in existing buildings from 14% to 44%, depending on building types and locations (Figure 38). The reduction percentage is higher in residential building at 27%-44% than commercial building at 14%-22% and industrial building at 16%-29%.

In residential buildings, upgrading the building envelope and systems was found to be very effective in reducing energy consumption. The proportions of energy reduction were higher in hot to mild climates compared with colder climates. Further discussion of the impact from each energy efficiency design strategy can be found in section 2.4.4. In commercial and industrial buildings, energy reduction proportions were lower than in residential buildings. This is probably because the internal load is more dominant.

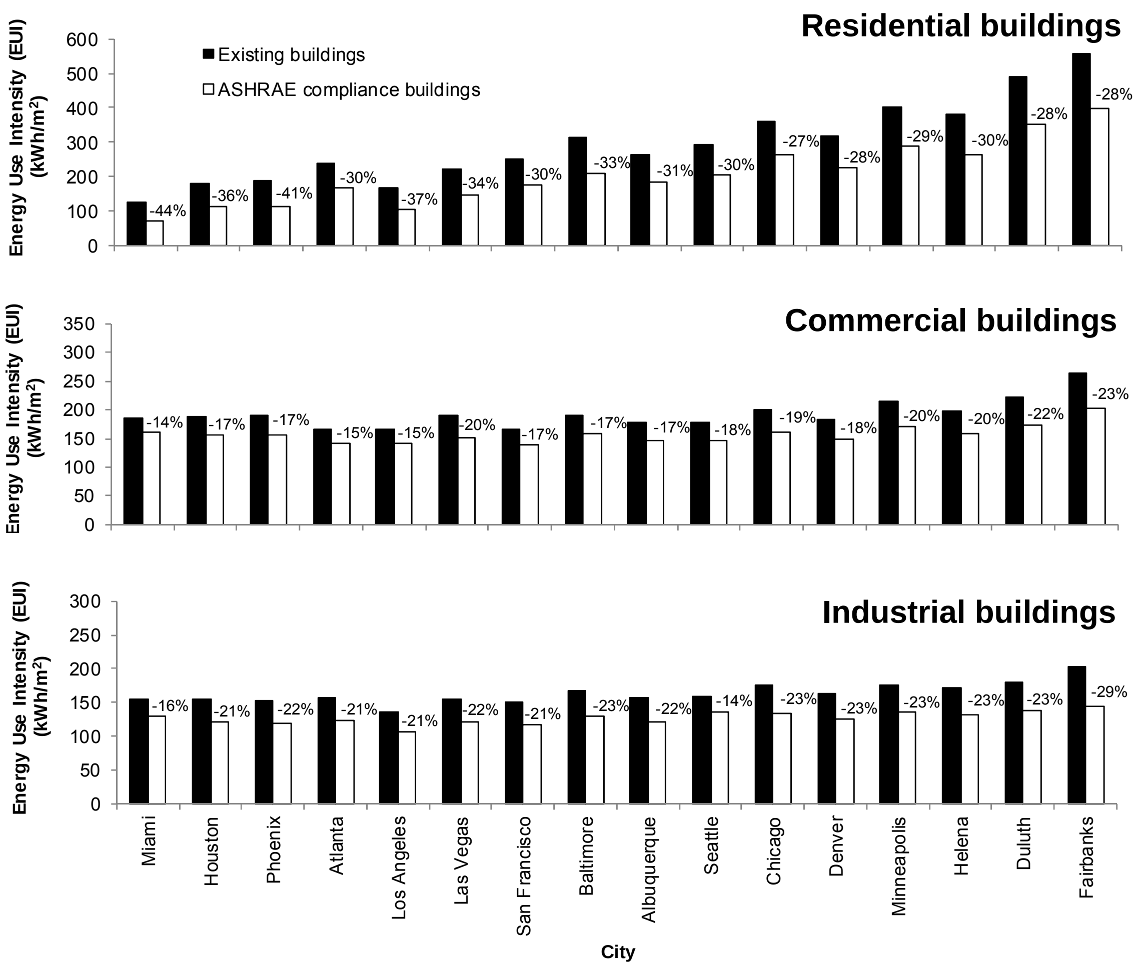


Figure 38. ASHRAE compliant building energy use intensities compared with existing conditions.

Annual electricity consumption in ASHRAE compliant buildings: For electricity consumption, compliance with the ASHRAE standard can bring annual electricity consumption down from 21% to 51% in residential buildings and 13%

to 23% in commercial and industrial buildings, depending on climates. Figure 39 shows results of small houses, medium office buildings, and industrial buildings.

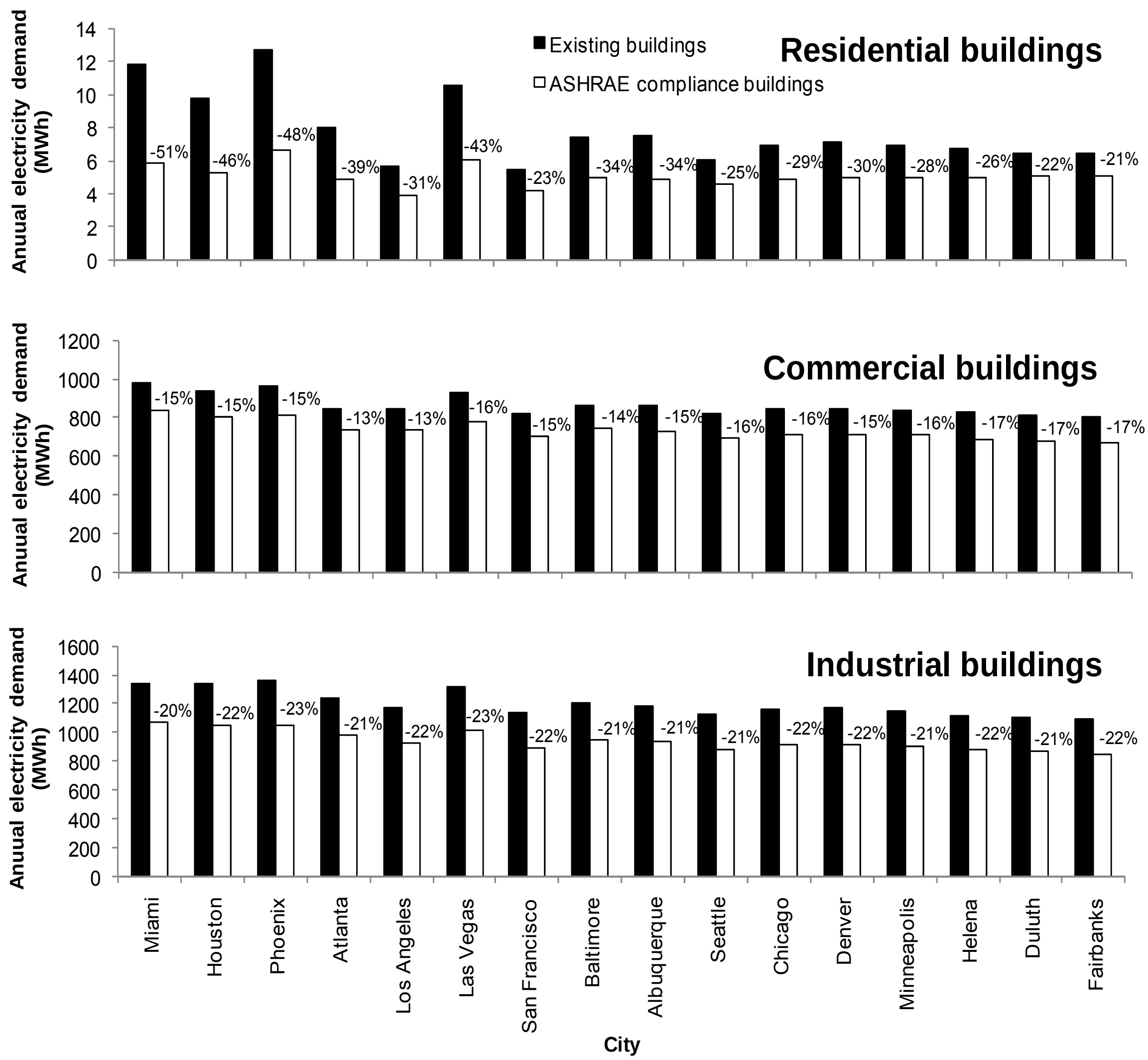


Figure 39. ASHRAE compliant building electricity consumption compared with existing conditions.

2.4.4 Potential of energy efficiency design strategies.

In this study, there were 12 to 13 strategies applied to the residential, commercial, and industrial buildings to quantify annual energy reduction and peak load prediction. Strategies are from beyond-codes or energy efficiency design practices. Some of them take into account the different requirements in the various weather zones. After simulation, unmet loads were checked to ensure that they did not exceed baseline building unmet loads by 50 hours.

a) Residential buildings.

There were 13 strategies used in the simulation as follows.

1. Super-envelope: Wall R = 7.044 m^2K/W (40 $ft^2{}°F·h/Btu$ – R40).
2. Super-envelope: Roof R = 10.566 m^2K/W (60 $ft^2{}°F·h/Btu$ – R60).
3. High efficiency glazing: ENERGY STAR exceptional window. Requirements for each climate zone is shown in Table 6.

Table 6. ENERGY STAR requirements for exceptional windows and glass doors.

City	Fenestration	
	U (W/m^2K)	**SHGC**
Miami	≤3.123	≤0.30
Houston	≤3.123	≤0.30
Phoenix	≤1.817	≤0.30
Atlanta	≤1.817	≤0.30
Los Angeles	≤1.817	≤0.30
Las Vegas	≤1.817	≤0.30
San Francisco	≤1.817	≤0.30
Baltimore	≤1.817	≤0.40
Albuquerque	≤1.817	≤0.40
Seattle	≤1.590	Any
Chicago	≤1.590	Any
Denver	≤1.590	Any
Minneapolis	≤1.590	Any
Helena	≤1.590	Any
Duluth	≤1.590	Any
Fairbanks	≤1.590	Any

4. Combination of 1, 2, and 3.

5. Thermal mass: Unfinished concrete floors and mass internal walls.
6. Daylighting: Side lit, 500 lux (50 fc). Switch: full, 2/3, 1/3, off.
7. Cooling system efficiency: SEER = 16.
8. Heating system efficiency: AFUE = 97.5.
9. Lighting Power Density (LPD): 3 W /m^2 (0.3 W /ft^2).
10. High efficiency appliances: Reduced load from 2 w/m^2 (0.2 W/ft^2) to 1 w/m^2 (0.1 W/ft^2).
11. Reset thermostat 1.1°C (2°F) higher in summer and 1.1°C (2°F) lower in winter.
12. Passive house: Combination of strategies.
    - Wall R = 7.044 m^2K/W (40 ft^2°F·h/Btu – R40).
    - Roof R = 10.566 m^2K/W (60 ft^2°F·h/Btu – R60).
    - Tight construction, perimeter infiltration < 0.01 CFM/m^2 exterior wall area.
    - Reduced internal loads: LPD 3 W /m^2, appliances 1 W /m^2.
    - Use solar hot water systems.
13. ZEB: Combination of strategies
    - Wall R = 7.044 m^2K/W (40 ft^2°F·h/Btu – R40).
    - Roof R = 10.566 m^2K/W (60 ft^2°F·h/Btu – R60).
    - Floor R = 5.283 m^2K/W (30 ft^2°F·h/Btu – R30).
    - South window U = 1.703 W/m^2K (0.30 Btu/ft^2°F·h) SHGC = 0.58.
    - North, west, and east window U = 1.306 W/m^2K (0.23 Btu/ft^2°F·h) SHGC = 0.27.
    - HVAC system efficiency factor: SEER = 16, AFUE = 97.5.
    - Low LPD at 3 W/m^2 and high efficiency appliances 1 w/m^2.
    - Use solar hot water systems.

b) Commercial and industrial buildings.

There were 12 strategies for small commercial buildings and 13 strategies for medium commercial buildings, big commercial buildings and industrial buildings used in the simulation.

1. Super-envelope: Wall R = 7.044 m^2K/W (40 $ft^2°F·h/Btu$ – R40)
2. Super-envelope: Roof R = and 10.566 m^2K/W (60 $ft^2°F·h/Btu$ – R60)
3. High efficiency glazing: ENERGY STAR exceptional window according to Table 6.
4. Combination of 1, 2, and 3.
5. Thermal mass: concrete floors and mass internal walls.
6. Daylighting: Side lit, 500 lux (50 fc). Switch: full, 2/3, 1/3, off.
7. Cooling system efficiency: EER 14.
8. Boiler efficiency 95%.
9. LPD: 30% reduction.
10. High efficiency appliances: Reduced load 4 W/m^2 in office space from 22 W/m^2 (2.2 W/ft^2) to 18 W/m^2 (1.8 W/ft^2).
11. Reset thermostat 1.1°C (2°F) higher in summer and 1.1°C (2°F) lower in winter.
12. Supply air temperature deck reset varied from 10°C (50°F) to16.1°C (61°F). This strategy is not applicable with small commercial buildings.
13. ZEB: Combination of strategies
    - Wall R = 7.044 m^2K/W (40 $ft^2°F·h/Btu$ – R40).
    - Roof R = 10.566 m^2K/W (60 $ft^2°F·h/Btu$ – R60).
    - Floor R = 5.283 m^2K/W (30 $ft^2°F·h/Btu$ – R30).
    - South window U = 1.7034 W/m^2K (0.30 $Btu/ft^2°F·h$) SHGC = 0.58.
    - North, west, and east window U = 1.306 W/m^2K (0.23 $Btu/ft^2°F.h$) SHGC = 0.27.
    - HVAC system efficiency: EER = 14, Boiler efficiency 95%.

- Lower LPD at 30% reduction and high efficiency appliances at 18 W/m^2.
- Use solar hot water systems

c) Impact of energy efficiency design strategies on each end-use energy consumption category.

All strategies explored in this section were applied to ASHRAE-compliant buildings. The Chicago results have been selected for discussion in this section because they represent both winter and summer conditions (Figure 40 through Figure 45).The results are as follows:

Architectural components

a. Super-envelope, wall insulation: Adding more wall insulation to an already well-insulated building can reduce heating load but not cooling load.
b. Super-envelope, roof insulation: Adding more roof insulation can bring heating energy consumption down in commercial and industrial buildings, but not in residential buildings.
c. High efficiency glazing: Using higher efficiency windows can reduce some cooling load, but they increase heating load in winter because heat from the sun is blocked from entering the building when it is available.
d. Combination of wall insulation, roof insulation, and high efficiency glazing: The combination of adding more insulation in the walls and roof and the use of higher efficiency windows together did not result in the sum of the three strategies' savings. It is better to select either adding more wall insulation or adding more roof insulation, depending on building types, sizes, and climates.

e. Thermal mass: Thermal mass strategy can help reduce heating load in winter in large buildings, but it increases heating load in small buildings, such as houses. In this study, thermal mass was applied to buildings by simply changing internal wall and floor to mass constructions. Proper design of thermal mass requires southern window exposures and good heating insulation. The exposure of thermal mass area to winter sunlight varies from climate to climate.
f. Daylighting: Daylighting strategy can help reduce lighting energy consumption as well as space cooling. This is because lower lighting load means lower heat dissipated from light bulbs, which decreases space cooling load. On the other hand, this results in a higher space heating load in winter, because internal load is reduced. Daylighting was more effective in commercial and industrial buildings than in residential buildings, because it helps in reducing energy used in lighting systems and has less impact on overall heating loads.

Building systems

g. Cooling system efficiency: Increased cooling system efficiencies can directly reduce energy use in cooling systems.
h. Heating system efficiency: Increased heating system efficiencies can directly reduce energy use in heating systems.
i. LPD: Reduced lighting power density can reduce energy use in lighting systems as well as in cooling systems, but they increase energy use in heating systems because internal load is reduced leading to higher heating energy consumption.
j. High efficiency appliances: The use of high efficiency appliances can reduce energy use in other system categories, including energy consumption from electric office appliances and other plug load equipment. Heat dissipating from this

equipment was also reduced, which led to energy reduction in cooling systems, but energy increases in heating systems.

Building management

k. Reset thermostat: Raising the thermostat temperature setting in summer and reducing the thermostat temperature setting in winter will reduce energy use both in cooling and heating systems.
l. Supply air temperature deck reset: Setting a higher temperature for cold deck reset temperature reduces energy use both in cooling and heating systems.

Combined strategies

m. Passive house: The passive house strategy in residential buildings deals with reducing building load, tightening building envelope, and using solar hot water systems and can reduce energy in all end-use categories.
n. ZEB: This combined strategy implements almost all available strategies, resulting in the lowest overall energy use compared with other strategies. This strategy can reduce energy in all end-use categories. ZEB also utilized solar hot water systems that eliminate energy used in domestic hot water systems and some part of the water heating service in large buildings.

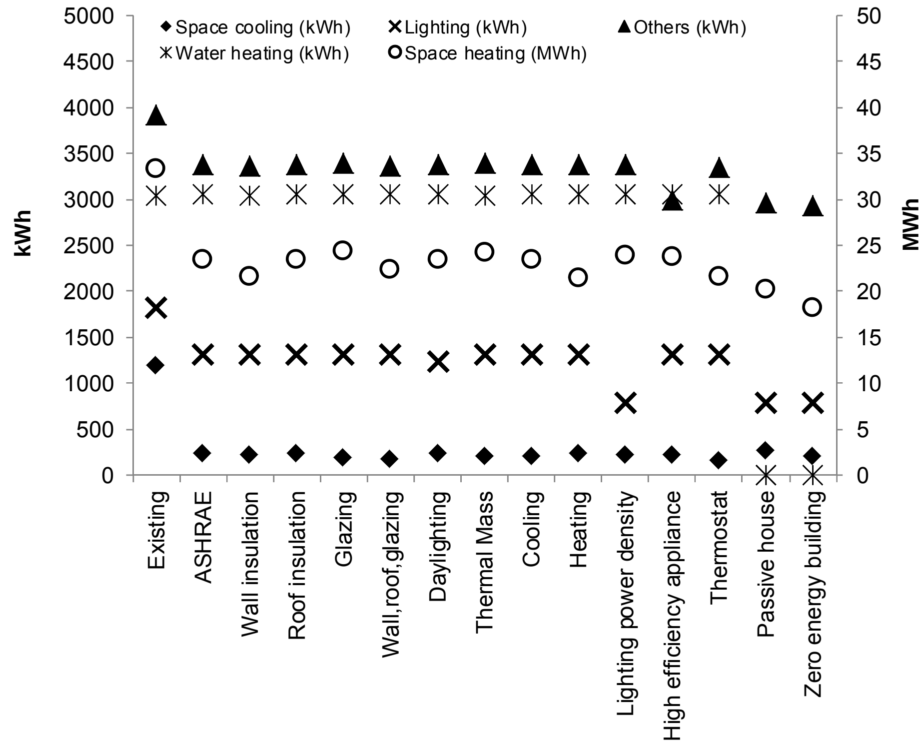


Figure 40. Impact of energy efficiency design strategies on each end-use energy consumption category in Chicago's small houses.

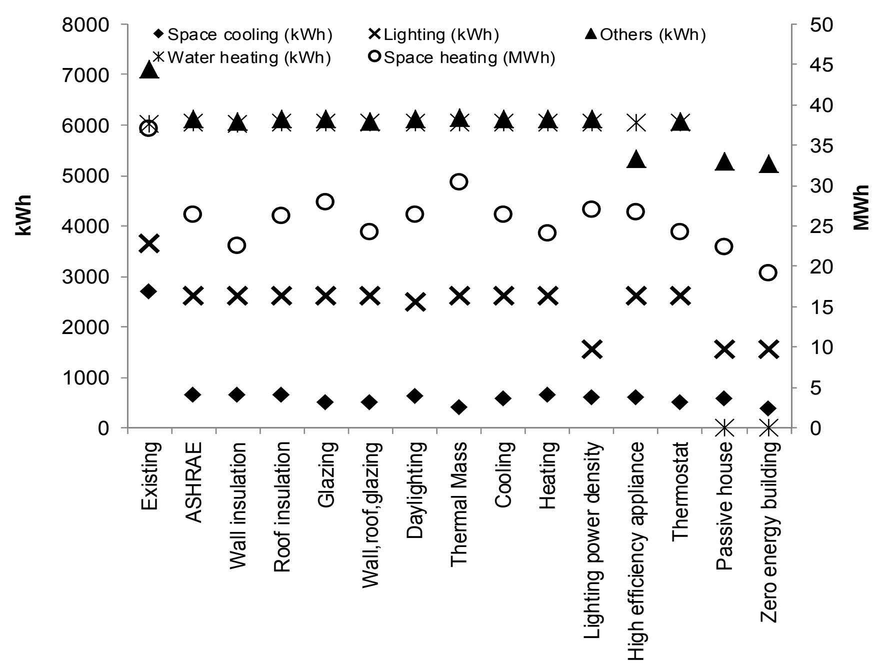


Figure 41. Impact of energy efficiency design strategies on each end-use energy consumption category in Chicago's medium houses.

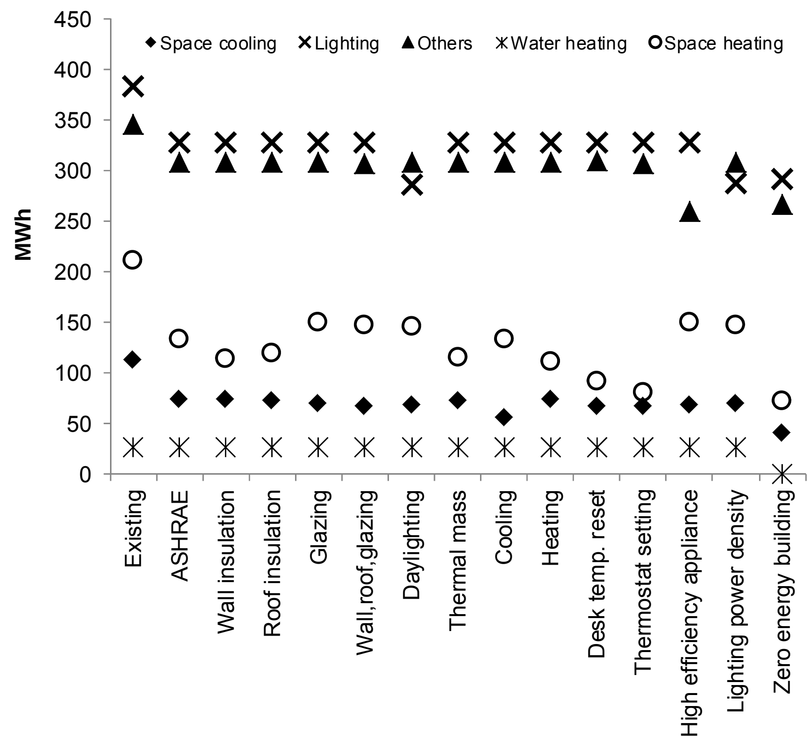


Figure 42. Impact of energy efficiency design strategies on each end-use energy consumption category in Chicago's small commercial buildings.

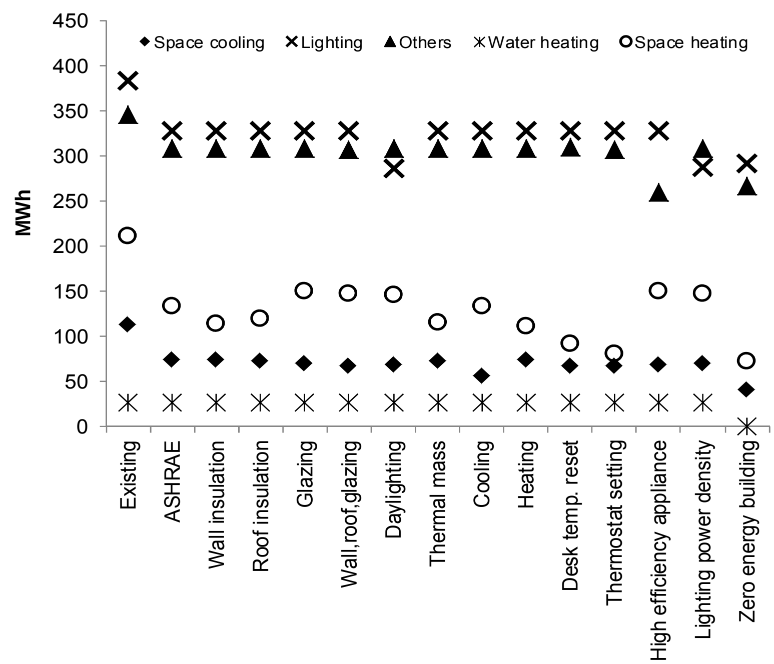


Figure 43. Impact of energy efficiency design strategies on each end-use energy consumption category in Chicago's medium commercial buildings.

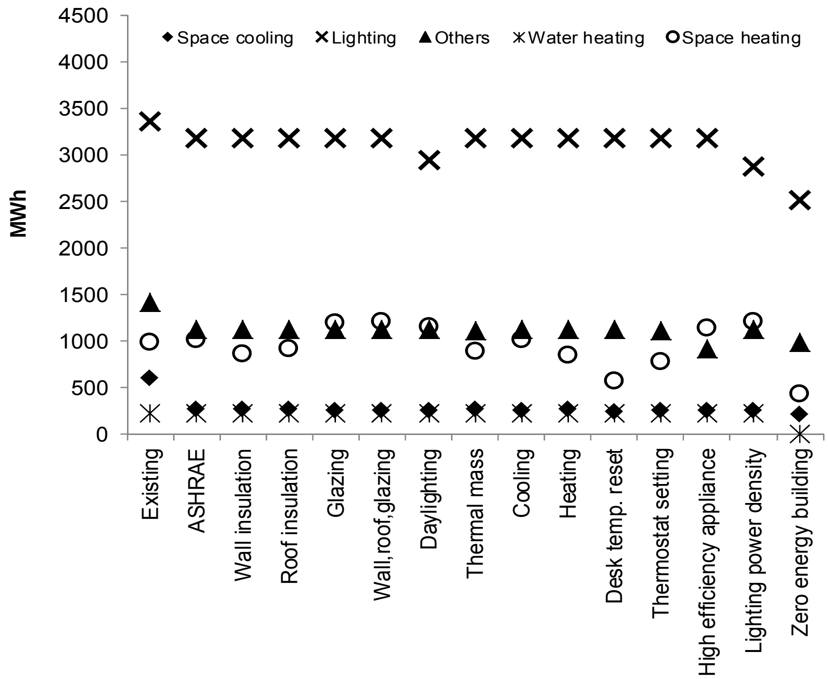


Figure 44. Impact of energy efficiency design strategies on each end-use energy consumption category in Chicago’s big commercial buildings.

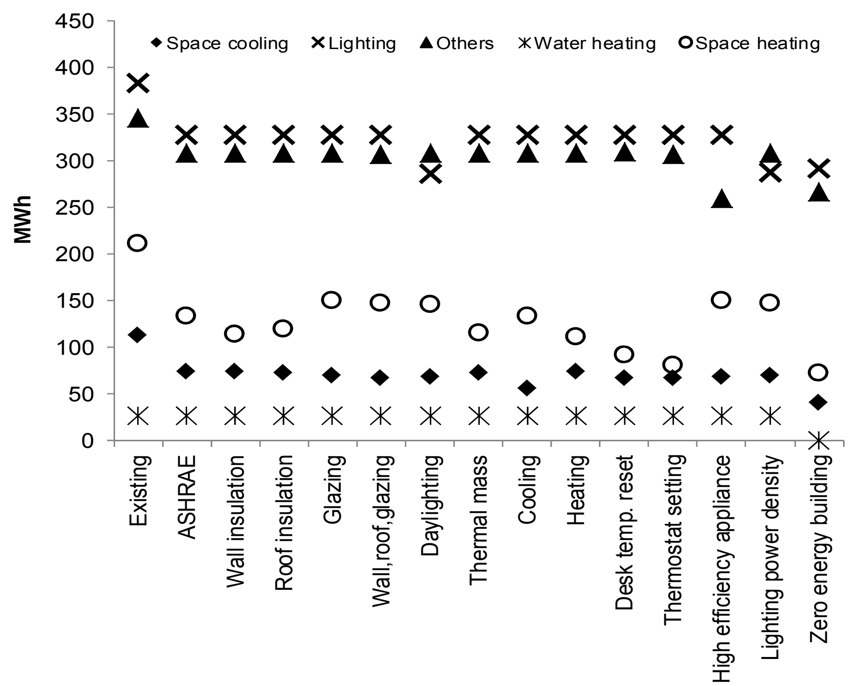


Figure 45. Impact of energy efficiency design strategies on each end-use energy consumption category in Chicago’s industrial buildings.

In other cities, energy reduction from applying each strategy to end-use energy followed the same trend as results shown from the Chicago climate. However, the magnitudes of impact are different.

d) Impact of energy efficiency design strategies on annual electricity consumption in residential buildings

In residential buildings, when energy efficiency design strategies were applied to ASHRAE-compliant buildings, electricity can be further reduced up to 17% (Figure 46).

- Applying more wall insulation or using higher performance glazing can bring electricity consumption down a little, but adding more roof insulation has no effect on reducing electricity consumption.
- The combination of adding more insulation to wall and roof and using higher performance glazing resulted in slightly more savings than was observed by adding their savings together directly.
- Daylighting has little effect on reducing annual electricity consumption.
- Thermal mass increases electricity use in cooling systems in the summer. Therefore, it increases electricity consumption in hot climates.
- Improving cooling efficiency from EER14.5 to 16 in residential buildings, has little effect on reducing annual electricity consumption.
- Increasing heating system efficiency from 0.90 to 0.975 has no effect on electricity reduction, because the energy source was natural gas.
- Reducing lighting power density and using high efficiency appliances resulted in more electricity savings than other single measures.

- Passive house and ZEB, which implement a combination of strategies, result in the largest electricity reduction among all strategies.
- In a residential building that is in use during the day, the percent of electricity reduction from applying energy efficiency design strategies is higher than a residential building with a typical pattern of use.

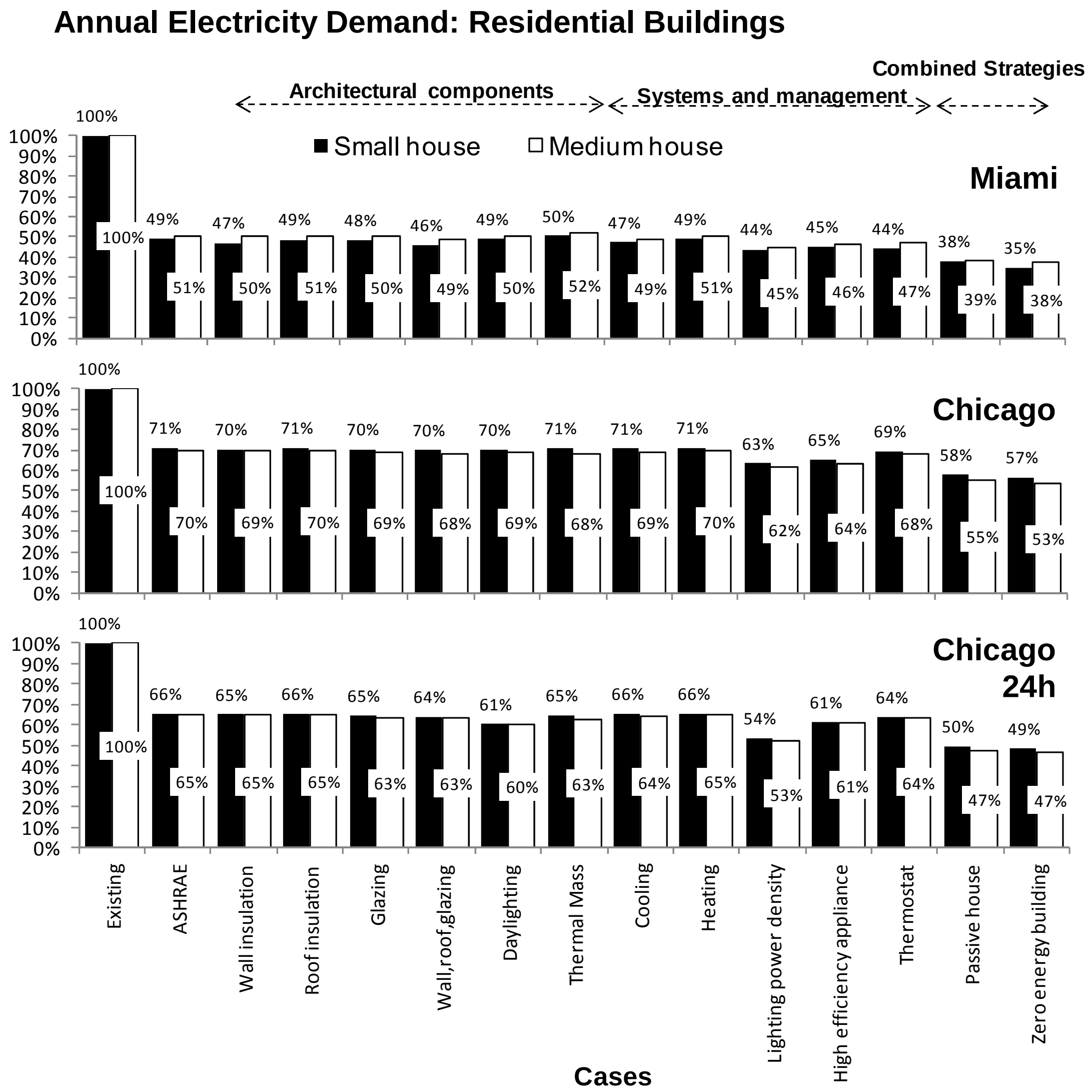


Figure 46. Comparisons of annual electricity consumption when different energy efficiency design strategies were applied to residential buildings.

e) Impact of energy efficiency design strategies on annual electricity consumption in commercial and industrial buildings

Electricity consumption can be further reduced up to 22% in commercial and industrial buildings when energy efficiency design strategies were applied to ASHRAE-compliant buildings (Figure 47).

- Adding insulation on building envelope has little effect on electricity consumption.
- Using higher efficiency glazing has little effect on buildings in hot climates but can help reduce electricity use in cold climate.
- Daylighting is an effective strategy in reducing electricity consumption especially in small office buildings.
- Thermal mass can help reduce electricity consumption by a small percentage, and it is more effective in one-story buildings, such as small office buildings or factory buildings, in this study.
- Upgrading cooling system efficiency can reduce more electricity use in hotter climates. Its electricity reduction in big office buildings was, however, small.
- Increased heating system efficiency has no effect on reducing building electricity use, because the heating system energy source was natural gas in all buildings in this study.
- Reducing lighting power density was found to be the best single strategy, especially in small office buildings.
- The second best single strategy was the use of high efficiency appliances, which is most effective in big office buildings.
- Setting the thermostat higher in summer and lower in winter was found to be effective in hot climates more than in cold climates.
- Resetting cooling desk temperatures was found to have very little, or in some cases, negative impact on electricity consumption.

- ZEB, which is the combination of numerous strategies, was found to be able to reduce electricity consumption 10%-25% in typical use schedule buildings.
- In buildings with high use or that operate longer than a typical schedule, the percentage of electricity savings in most cases was higher than buildings that operate with a typical schedule.

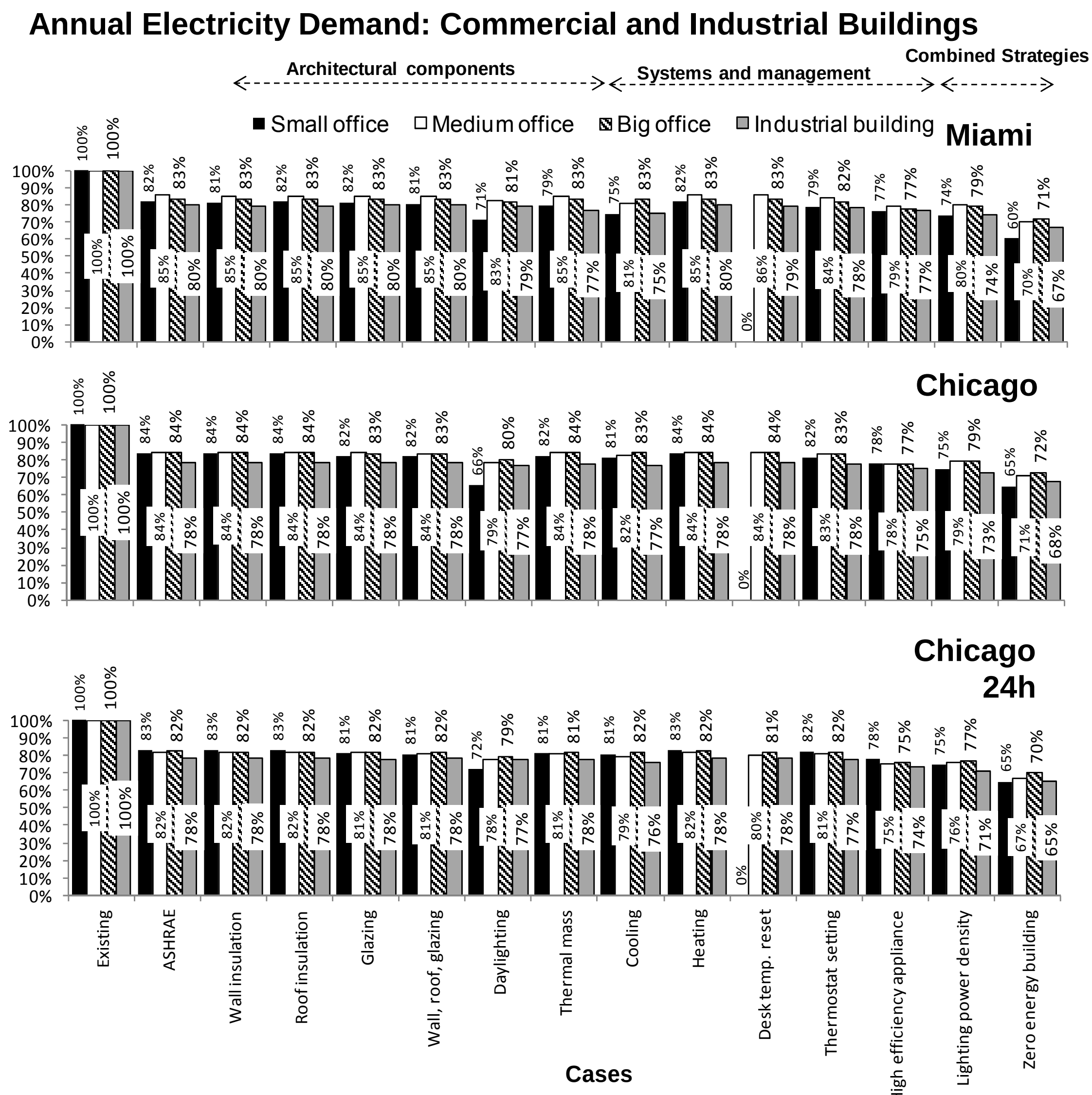


Figure 47. Comparisons of annual electricity consumption when different energy efficiency design strategies were applied to commercial and industrial buildings.

f) Impact of energy efficiency design strategies on peak electricity demand in residential buildings

ASHRAE compliant buildings were found to be able to reduce electricity peak demand approximately 40%-50% in residential buildings. Reducing lighting power density is the best single strategy that can reduce peak load in buildings located in cold climates. In hot climates, increased building insulation and glazing performance reduced peak electricity demand the most (Figure 48).

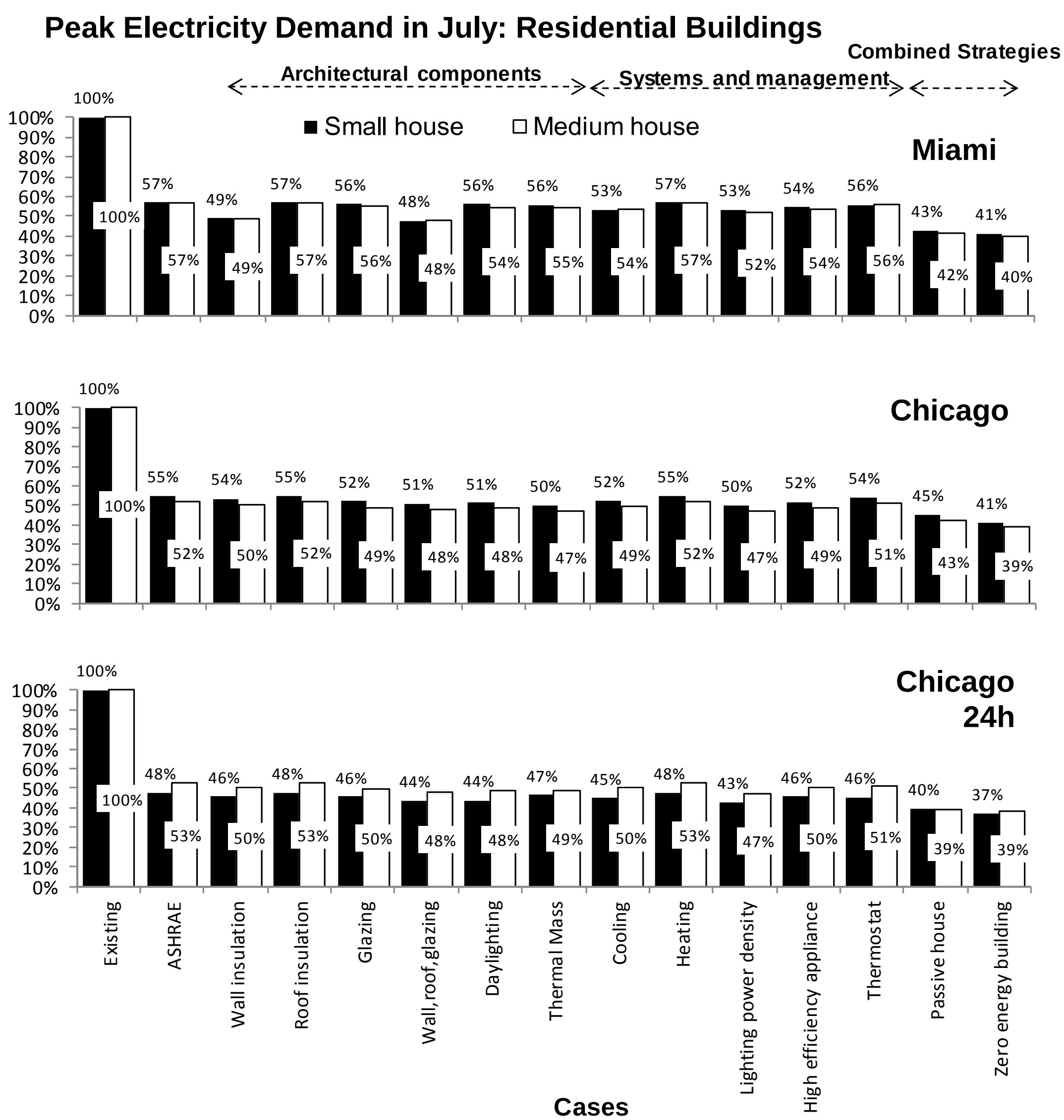


Figure 48. Comparison of peak electricity demand when different energy efficiency design strategies were applied to residential buildings.

g) Impact of energy efficiency design strategies on peak electricity demand in commercial and industrial buildings

ASHRAE compliant buildings were found to be able to reduce electricity peak demand approximately 10%-30% in commercial and industrial buildings. Improving cooling system efficiency is the best single strategy in small office buildings, medium office buildings, and factory buildings, especially in hot climates. Daylighting is also one of the best single strategies in cold climates for small and medium commercial buildings (Figure 49).

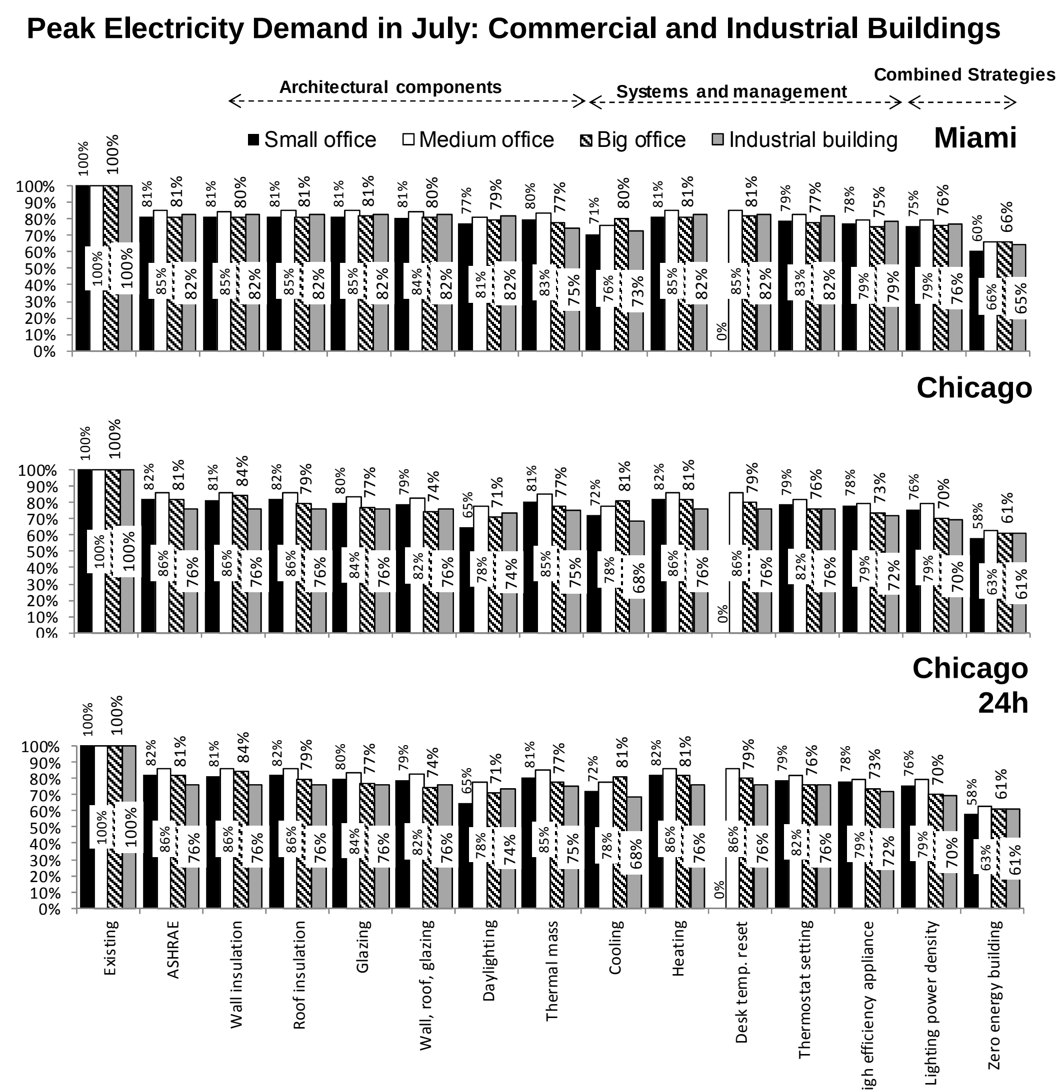


Figure 49. Comparison of peak electricity demand when different energy efficiency designs strategies were applied to commercial and industrial buildings.

In big office buildings, chilled water-cooling systems were used. These systems have high efficiency, therefore, increasing the system efficiency even more did not result in much peak demand reduction. The best single strategy in big office buildings is using high efficiency appliances.

2.5 Conclusions

In this chapter, the background of energy efficiency design strategies was presented. Methodology used in simulating buildings in existing condition, compliance with ASHRAE standard, and when applied, various energy efficiency design strategies were demonstrated. In developing baseline models, various sources were used such as EIA national energy consumption survey, Building America research project, DOE commercial reference buildings, and ASHRAE 90.1 and 90.2 standards. Buildings were grouped into three types: residential, commercial, and industrial. These baseline buildings represent typical building construction, and use patterns were used as benchmarks to track energy reduction from energy efficiency design strategy options. Buildings were modeled using TMY3 weather data for 16 cities representing climate in eight weather zones and their sub-zones. Normal and 24-hour schedules available in eQUEST software for each building type were used.

From the simulation, residential building energy use largely depends on external climate. Space heating is a major energy consumer in this type of building, which mostly depends on natural gas. The energy use intensity pattern was roughly consistent with the national averages. For electricity use, building equipment (including lighting systems) had the largest consumption. Commercial building energy use compared with the reference buildings were lower than the reference buildings by 1% to 15%. The majority of energy used in commercial buildings is electricity except for buildings in very cold climates. Internal loads from lighting, appliances, and equipment were dominant. Industrial buildings that process load were excluded from the simulations; they use a similar proportion of electricity to natural gas as commercial buildings. Lighting systems used the highest portion of electricity in both of these types of buildings.

ASHRAE standards were found to be able to reduce energy consumption in existing buildings from 27% to 44% in residential buildings, 14% to 22% in commercial buildings, and 16% to 29% in industrial buildings. In colder climates, the percentage gets lower for residential buildings, but gets higher for commercial and industrial buildings. For electricity use, ASHRAE compliant buildings were found to be able to reduce annual electricity consumption from 21%-51% in residential buildings and 13%-23% in commercial and industrial buildings. Peak electricity demand reduction was found to be approximately 43%-51% in residential buildings and 12%-28% in commercial and industrial buildings.

After energy efficiency design strategies were applied to ASHRAE compliant buildings, electricity could be reduced further up to 17% in residential buildings by the combination of strategies such as passive house and ZEB. The best single energy efficiency design strategy for reducing annual electricity consumption in residential buildings was reducing lighting power density and using high efficiency appliances. The percentage of electricity reduction was higher in colder climates and in 24-hour use buildings. In commercial and industrial buildings, annual electricity consumption could be reduced 10%-22% when combinations of energy efficiency design strategies such as ZEB, were applied to ASHRAE compliant buildings. Daylighting, reducing lighting power density, and increasing appliance efficiency were found to be effective single strategies.

For peak electricity demand reduction, ZEB strategy was the best strategy in all kinds of buildings. In residential buildings, adding building insulations and increasing glazing performance were found to be the best single strategies in hot climate. In cold climate, reducing lighting power density was found to be the best single strategy. In commercial and industrial buildings, increase cooling system efficiency was the best single strategy in small office buildings, medium office buildings and factory buildings. In big commercial buildings, using high efficiency appliances was the best single strategy.

Results in this chapter show trends of energy and electricity behaviors after energy efficiency design strategies were implemented and can provide more understanding of the impact that each strategy can cause in different kinds of building types, building sizes, use schedules, and climates. In chapter three, results of energy efficiency design strategies implemented with grid-connected PV systems are described. Then their performances in reducing annual electricity consumption, reducing peak electricity demand, and increasing building electricity load met are prioritized.

CHAPTER 3
THE GRID-CONNECTED PHOTOVOLTAIC SYSTEM AND ITS IMPACT ON THE ELECTRIC GRIDS

The potential of grid-connected PV systems vary from location to location. Basic information about the potential of PV systems involving electricity generation and resource or solar radiation availability is presented first. Current and future PV technologies, as well as the transformation of electric grid, are then discussed. Finally, potential and impact of grid-connected PV systems when implemented with energy efficiency design strategies in various building types, sizes, use schedules, and climates are presented.

3.1 PV Systems Potential

3.1.1 The photovoltaic effect.

The photovoltaic effect was observed by Edmund Becquerel in 1839 when he exposed an experimental electrolytic cell made up of two metal electrodes to white light, and discovered that a weak electric current could be produced (Becquerel, 1839). He named the phenomenon "photovoltaic." "Photo" means light and "voltage" is the unit of electrical force. The phenomenon was explained later by Albert Einstein in 1905 (Einstein, 1905), winning him the Nobel Prize in 1921. Einstein described light as being made up of discrete pockets of energy called quanta or photons. When light shines on metal, photons penetrate it and knock electrons off atoms creating electric current. The higher the frequency, the more electrons are coming off the metal. Bell Labs introduced the first commercial solar photovoltaic product that produced a useful amount of electricity in 1954. At that time, the PV price was too high for commercial use. PV systems were used in small-scale scientific and commercial applications, including the space program. The energy crisis of the 1970s created an interest in using PV to produce electricity. PV systems were made feasible by later research and development activities for off-grid or stand-alone applications in remote areas.

Most PV materials are made from silicon, which is a semiconductor. At an absolute temperature, silicon acts like an insulator because all electrons in one atom are perfectly bonded to their other four neighbors. There is no free electron to create electric current. When the temperature increases, some electrons will have enough energy to free themselves from their valence band and jump into the conduction band, making it act like a conductor. When sunlight strikes the surface of a PV cell, photons from sunlight can give energy to electrons in the cell and the electrons can be free from their atoms. For silicon, this energy is called band gap energy and is equal to 1.12 eV. To create directional flows, silicon is doped with phosphorus and boron. A typical silicon PV cell is composed of a thin wafer consisting of an ultra-thin layer of phosphorus-doped (Negative or N-type) silicon on top of a thicker layer of boron-doped (Positive or P-type) silicon. An electrical field is created near the top surface of the cell where P-type silicon and N-type silicon are in contact, called the P-N junction. Directional flows are created so that electrons will not fall back into their atoms and move to the same direction creating an electric field, resulting in a flow of current when the PV cell is connected to an electrical load.

3.1.2 The solar resource.

The vast amount of energy from the sun comes to the earth in the form of solar radiation consisting of electromagnetic waves. The sun is approximately 149.48 million kilometers from earth on average, but because the earth's orbit is slightly elliptical, the distance varies throughout the year. The sun is closest to the earth in June and farthest in December. Average extraterrestrial solar irradiation energy at normal incidence on a surface just outside the earth's atmosphere is called the solar constant (E_{sc}). This value is equal to 1366.1 W/m^2

(ASTM Standard, 2006; Christian A. Gueymard, 2006) and varies slightly at ±3% because of earth-sun distance and sun spot activities (Duffie & Beckman, 2006).

At the location just outside the earth's atmosphere, there is no air mass. AM 0 refers to extraterrestrial radiation where there is no atmosphere. The length of the sun's ray path through the earth's atmosphere to reach the earth's surface when the sun is directly above the head is equal to AM 1. For most PV systems, an air mass ratio of 1.5 – which is equal to the sun being 48.19 degrees above the horizon – is assumed to be the standard (ASTM Standard, 2006; ASTM Standard G173-03, 2003; C. A. Gueymard, Myers, & Emery, 2002). The solar spectrum at AM 1.5 is shown in Figure 50. For an AM 1.5 spectrum, 2% of the incoming solar energy is in the ultraviolet (UV) portion of the spectrum, 54% is in the visible, and 44% is in the infrared (IR). Photons with wavelengths longer than 1.11 μm do not have enough energy for electrons to free themselves (20.2% of the incoming solar energy). Those with shorter wavelengths cannot use all of their energy, accounting for another 30.2%. Solar spectrum available to excite electrons in silicon decreased to 49.6%, which are those with a wave length range from 380-789 nm (blue-red) (ERDA/NASA, 1977). This range of wave consists of photons with enough energy for electrons in silicon to jump from their valence band to conduction band as discussed previously.

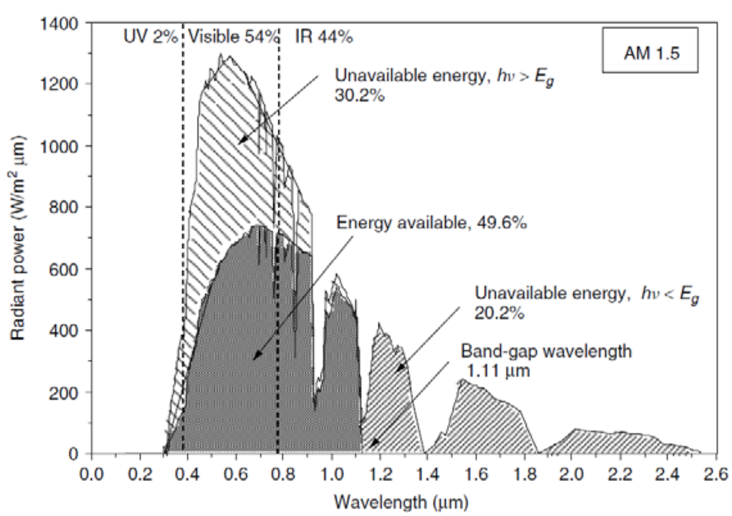


Figure 50. Solar spectrum at AM 1.5 (Masters & Wiley, 2004).

Photovoltaic systems work by converting solar radiation or solar energy into electric current. The amount of electricity output is directly proportional to the intensity or the amount of solar radiation. However, the amount of solar radiation that arrives at the earth's surface is not constant, and depends upon region, geography of location, time of day, time of year, cloud amount, and atmospheric aerosol condition. To evaluate if a PV system is suitable for a specific location, the amount of solar radiation levels measurable at that location is needed. The accuracy of system size estimation and optimal operation management depends on the accuracy and details of solar radiation data that is available.

The total or global solar radiation striking a PV system has three components: direct beam radiation, diffuse radiation, and reflected radiation. At weather stations, diffuse radiation and global or total solar radiation are usually measured using pyranometers that respond to solar radiation from a half spherical field of view. To measure diffuse radiation, a pyranometer is shaded from direct sunlight by a shading ring. Direct beam radiation can be calculated by subtracting the total solar radiation with the diffuse solar radiation or it can be directly measured. Pyrheliometers measuring solar radiation in a narrow field of view are used to measure direct normal incidence solar beam. They are installed with solar tracking systems, which always direct the instrument toward the sun.

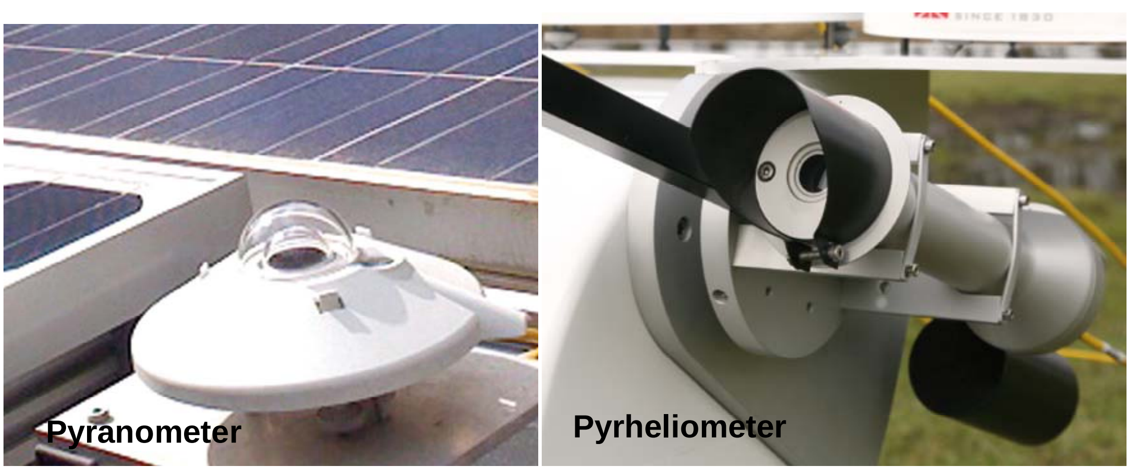


Figure 51. Pyranometer used to measure global radiation and pyrheliometer used to measure direct normal beam radiation (Kipp and Zonen, 2011).

However, the equipment used to collect solar radiation data is not installed at every ground weather station because of budget and maintenance constraints. Scientists have developed several mathematical models to predict the available solar radiation for the ground stations without solar radiation measurement equipment. These models rely on other weather data such as pressure and amount of cloud cover.

a) National solar radiation database (NSRDB) weather data.

Solar radiation data in the U.S. is available from NSRDB. The database was developed by the NREL and the National Climatic Data Center (NCDC) and provides hourly solar irradiance and other climate parameters for public use. Data from 1961 to 1990 are available for 239 locations and data from 1990 to 2005 are available for 1,454 locations. Among these locations, only 40 stations have solar radiation measurements. At other locations, solar radiation data are estimated using calculations based on other weather parameters measured at ground weather stations. Examples of mathematical models for the calculations include the METSTAT model developed for NSRDB's Typical Meteorological Year (TMY) data set (Maxwell, 1998), and the NRCC model developed at the Northeast Regional Climate Center (NRCC) by Belcher and DeGaetano (Belcher & DeGaetano, 2007). The available solar radiation measurements from 40 stations are used to validate these solar radiation models.

b) Typical Meteorological Year (TMY).

Weather data at each location varies from year to year. To obtain average building performances from simulation, several years of weather data should be used. However, using several years of weather data is time consuming; therefore, a TMY is developed and normally used as a representative of weather conditions at a specific location in building simulation programs. The TMY is composed of hourly weather data, such as temperature, humidity, solar radiation, wind speed, and wind direction, for 12 months. Each month was selected from several years of measurements using statistical methods, with the condition that it represents the most typical weather pattern of that month.

Typical Meteorological Year, version 2 (TMY2) provided from NSRDB is generated from 30 years of data from 1961 to 1990, using the Sandia method (Hall, Prairie, Anderson, & Boes, 1978) and available for 239 locations in the United States. The statistical method used to select the typical month is based on nine daily weather values such as daily maximum, minimum, and mean dry bulb temperature, the maximum and mean wind velocity, and the total global horizontal solar radiation. The latest data set called Typical Meteorological Year, version 3 (TMY3) contains weather information including solar radiation data at 1,454 ground weather stations throughout the country. Typical month weather data is selected from 15 years of measurements between 1991 and 2005.

For electricity output prediction from PV systems, the TMY weather data format might not be suitable to use for simulations because it cannot capture the availability, variability, and uncertainty of solar power that can vary from day to day and year to year (Dean, 2010; Storck, McCaa, Eichelberger, & Etringer, 2010; Yimprayoon & Navvab, 2011b). However, for initial evaluation, the TMY dataset is normally used because of the convenience in getting the data and time spent in simulations.

c) Satellite derived weather data.

At locations away from ground weather stations, data from the nearest station, or alternatively, estimates based on the interpolation data between stations, are used. The problem of using data generated in this way is that the accuracy of the data decreases with distance from or between ground weather stations. A method to estimate solar radiation based on data from meteorological satellites has been developed. An example is the State University of New York at Albany (SUNYA) model developed by Perez et al. (Perez et al., 2002). In the SUNYA model, satellite images are used to derive solar radiation data that is time and place specific. These satellites are geostationary satellites that stay fixed over one spot directly above the equator to monitor the earth's atmosphere. The geostationary satellite data offers the advantages of wider geographic coverage with high-resolution images typically at 1 to 10 square kilometers per pixel. They repeatedly scan the earth's image, typically at 30 to 60 minute intervals.

Mathematical models are developed to generate high-resolution solar radiation resource maps based on this data. Solar radiation data generated by the traditional models METSTAT and NRCC, and solar radiation data generated by the satellite based model, were evaluated in 2005 by Mayer et al. (Myers, Wilcox, Marion, George, & Anderberg, 2005). The results demonstrated that the performance of these models was remarkably similar. However, when the distance between the site and the ground weather station is more than 34 kilometers, the solar radiation data derived from satellite images using algorithms like SUNYA are more accurate than using the nearest weather station data or the interpolation data between stations (Perez, Seals, & Zelenka, 1997).

Recently, specific location weather data sets derived from satellite images have become available. Examples of satellite-derived weather data are available from SolarAnywhere® (Clean Power Research, 2012) and 3Tier (3TIER Inc., 2012). Weather data sets derived from satellite images, for example, the SolarAnywhere® data set, include hourly global horizontal irradiance (GHI), direct normal irradiance (DNI), wind speed, and ambient temperature estimates for the specified location. These data from 1998-2007 are available for free. More recent data, as well as seven-day forecast data, are available with fees. The spatial resolution of the data is available at approximately 10 km x 10 km in the form of satellite grid tiles (Figure 52).

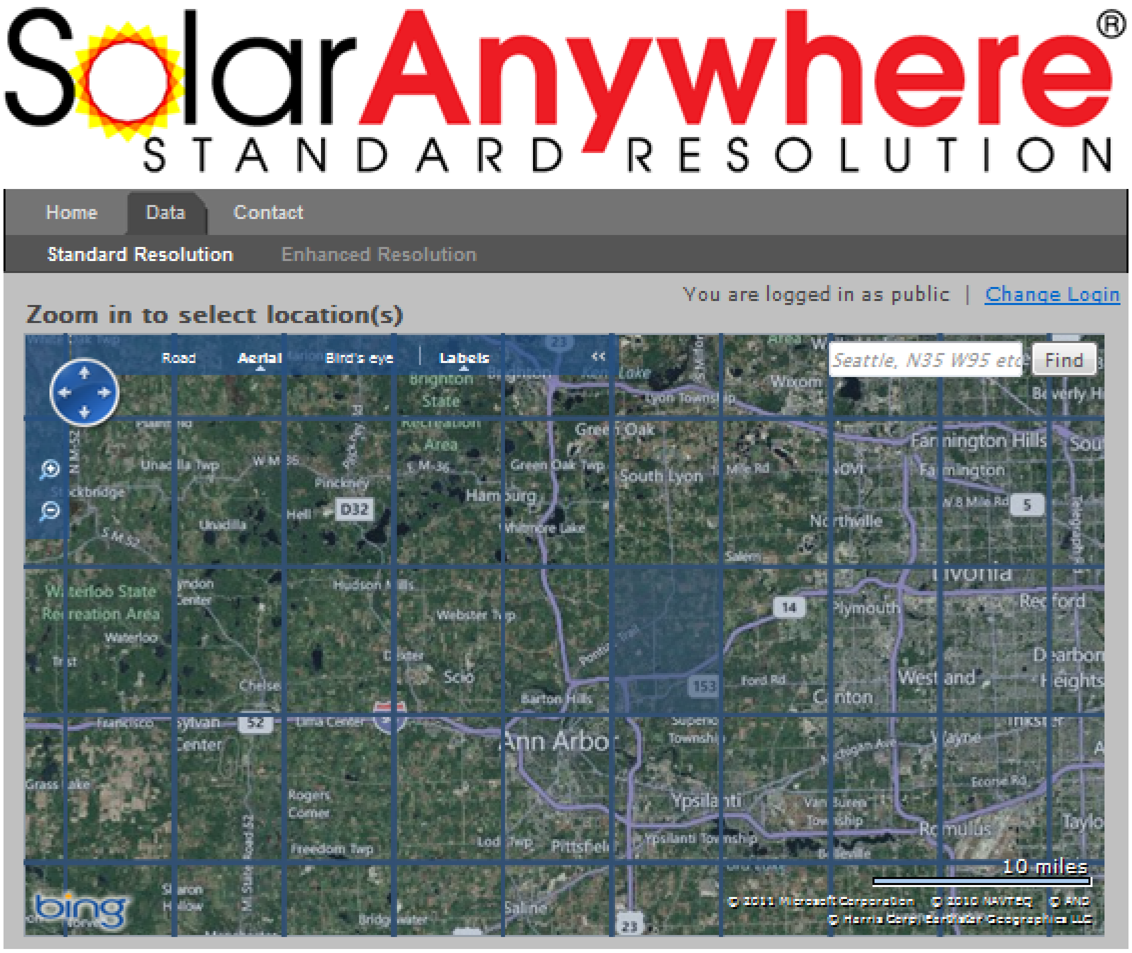


Figure 52. SolarAnywhere® data set grid tiles (Clean Power Research, 2012).

The NREL maintains and provides U.S. Solar Radiation Resource Maps. In Figure 53, the annual average daily solar resource is shown for latitude tilt PV systems with the resolution at 10 km x 10 km grid. The map is made for the U.S. DOE using a satellite model data set through collaboration with the State University of New York/Albany, the NREL, and other universities (Perez, et al., 2002). It can be seen that local weather plays an important role in how much solar radiation can reach each location. The amount of solar energy available in some parts of Texas is the same magnitude as some parts of North Dakota where the latitude difference is more than 15°.

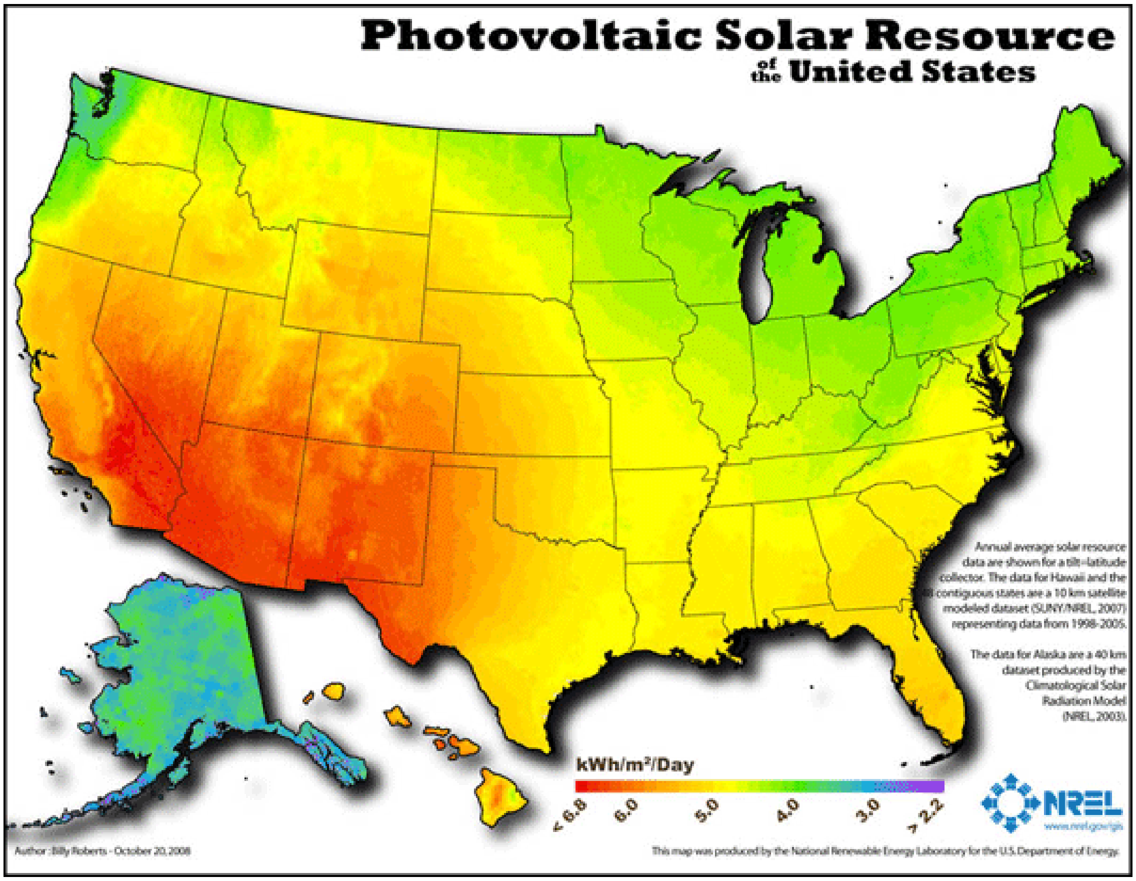


Figure 53. Solar resource map (NREL, 2011b).

d) Solar radiation on tilted surfaces.

The incident solar radiation on tilted surface is the sum of beam radiation, diffuse radiation, and reflected radiation (Figure 54).

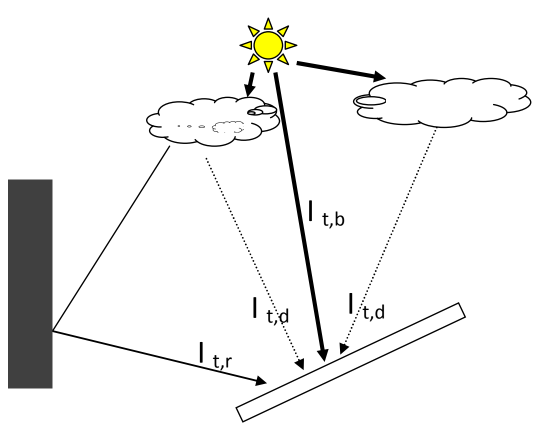


Figure 54. Solar radiation components on tilted surfaces.

Total solar radiation falling onto tilted surfaces can be written as:

$$I_T = I_{T,b} + I_{T,d} + I_{T,r} \quad (4)$$

Where

I_T = Total solar radiation on tilted surface (W/m^2)

$I_{T,b}$ = Beam radiation on tilted surface (W/m^2)

$l_{T,d}$ = Diffuse radiation on tilted surface (W/m^2)

$I_{T,r}$ = Reflected radiation from surroundings on tilted surface (W/m^2)

Normally, solar radiation dataset available from many sources comes in the form of direct normal beam radiation and horizontal global radiation. Direct normal beam radiation is the amount of solar radiation measured at the direct normal angle to the incoming beam. If direct normal beam radiation (I_{bn}) is known, the calculation of the amount of direct beam that falls onto tilted surfaces is straight forward and equal to $I_{bn} \cos\theta$ where θ is the incident angle of solar beam on the tilted surface (Figure 55). If I_{bn} is unknown, it can be estimated using other weather parameters.

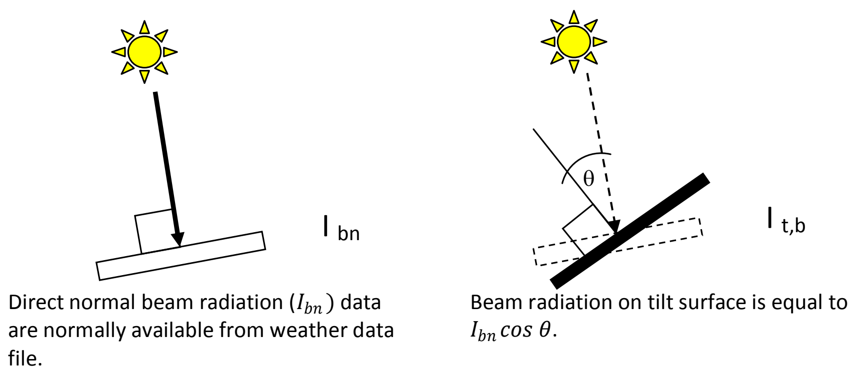


Figure 55.The calculation of beam radiation on tilted surface when direct normal beam radiation is known.

The diffuse radiation part is where different solar radiation models treat the calculation differently. Diffuse radiation models are generally composed of two to three parts which are isotropic part, circumsolar diffuse part, and horizon brightening part. Isotropic is the radiation part that the surface received uniformly from entire sky dome. The circumsolar diffuse is the part of sky concentrated around the sun onward. The horizon brightening is the part that concentrates near the horizon. The isotropic diffuse radiation depends on surface sky view factor. The circumsolar diffuse is treated as the same direction from the sky as the direct normal beam. The horizon diffuse is taken into account the albedo of the ground as well as the reflected radiation that assume the ground in front of tilted surfaces. Equation (4) becomes:

$$I_T = I_{bn}R_b + (I_{d,iso}F_{iso} + I_{d,cs}R_{d,iso} + I_{d,hz}F_{hz}) + \rho I_r F_r \quad (5)$$

Where

I_T = Total solar radiation on tilted surface (W/m^2)

I_{bn} = Direct normal beam radiation (W/m^2)

$l_{d,iso}$ = Diffuse isotropic radiation (W/m^2)

$l_{d,cs}$ = Diffuse circumsolar radiation (W/m^2)

$l_{d,hz}$ = Diffuse horizon brightening radiation (W/m^2)

I_r = Reflected radiation from surroundings (W/m^2)

F_{iso} = Radiation view factor from the sky to the surface

F_{hz} = Radiation view factor from the horizon portion to the surface

F_r = Radiation view factor from ground to the surface

R_b = Ratio of beam radiation falling onto the tilted surface to that on the horizontal surface.

$R_{d,iso}$= Ratio of diffuse isotropic radiation falling onto the tilted surface to that on the horizontal surface.

ρ = Ground albedo

Equation (5) is the basic model form with variations to calculate total radiation on tilted surfaces. These models are usually called transposition models or plane of array models. Many models have been developed. Models that are available in the simulation software used in this study are further discussed in section 3.1.5.

3.1.3 PV technologies.

PV cells are made of semiconductor materials that can absorb photons from solar energy and produce free electrons using the photovoltaic effect. There are a number of ways to categorize PV technology as follows:

- **By thickness:** PV can be divided into two types, one with 180-500 µm thickness, which is made from bulk materials cut into wafers, and thin film with 1–10 µm thickness. Thin-film requires much less material and is very light. It is semitransparent, making it possible to apply onto windows or use in multi-junction cells. However, its efficiency is less than conventional thick silicon cells and is also less stable over time.
- **By how atoms are bonded**: Atoms arranged in an orderly repeating pattern are called crystalline structure. Crystalline PV is divided into sub-categories, which are monocrystalline, multicrystalline (1 mm to 10 cm in crystalline size), poly-crystalline (1 µm to 1 mm in crystalline size), and micro-crystalline (less than 1 µm crystalline size). Those with no single-crystal regions are called amorphous structures, such as amorphous silicon.
- **By whether the p-n junction is made of the same materials:** Homojunction photovoltaics are those PVs with the p–n junction made of the same material. When the p-n junction is formed between two different materials, they are called heterojunction. Multijunction cells are made of a stack of p–n junctions with different materials. They are also called cascade or tandem cells. Multijunction cells are designed to capture solar energy at different wavelengths using different materials leading to a very high efficiencies cell.

The majority of PV cells have been produced based on silicon. Silicon makes up of 27% of the earth's crust and is the second most abundant element beside oxygen. The reason why silicon is a dominant material in the PV industry is that first, it is a semiconductor with good stability and strength sets of chemical, physical, and electrical properties. Second, the same strength properties also make silicon a perfect material for the larger microelectronics industry. PV, which is a smaller industry, can use waste silicon from microelectronics production processes.

The band gap energy for silicon is 1.12 eV and corresponds to solar wavelength at 1.1 μm. Wavelength below this number does not have enough energy to knock electrons out of the valence band in silicon. However, wavelength above 1.1 μm will have energy more than required, and the excess energy is wasted as heat. Other materials have been developed to be used as PV cells. These materials have different band gap energy, and thus can make use of different portions of solar radiation.

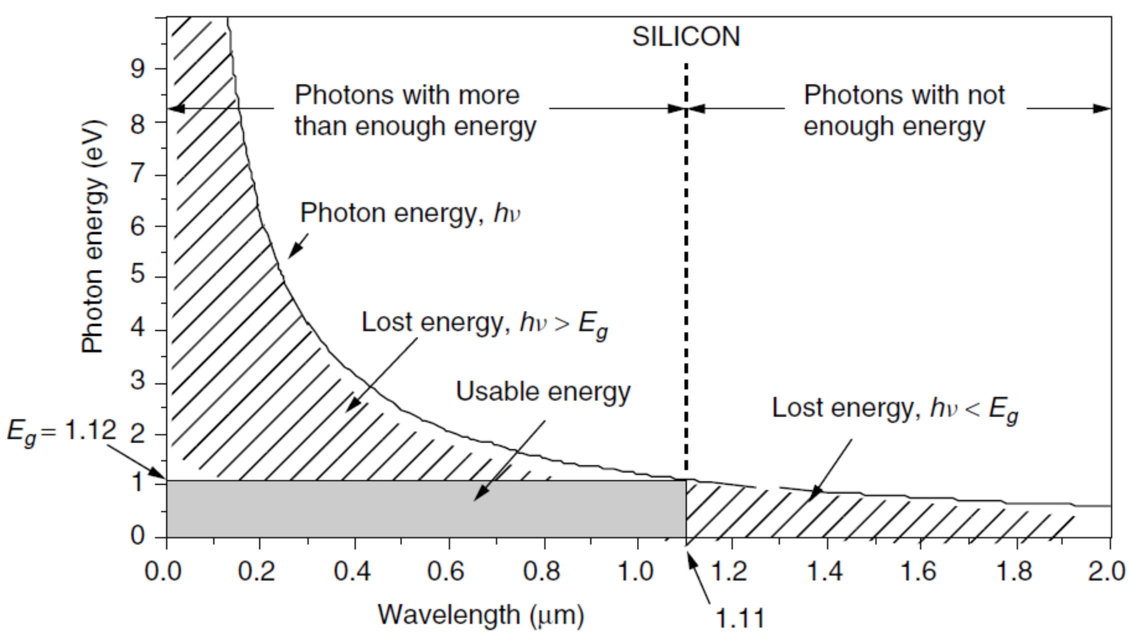


Figure 56. Usable solar energy in silicon based PV (Masters & Wiley, 2004).

Another tradeoff for materials used is that materials with low band gap energy give more current with less voltage, while materials with high band gap energy result in less current and higher voltage. Usually the band gap energy is between 1.2 eV and 1.8 eV, which will result in the highest power and efficiency.

a) Crystalline silicon (c-Si).

There are two main types of crystalline silicon used for PV cells: monocrystalline silicon (mono-Si) and poly- or multicrystalline silicon (poly-Si or mc-Si). The silicon cells must be wired together in series and then covered with layers of glass, Ethylene Vinyl Acetate (EVA), or polymers for weather protection (Figure 57).

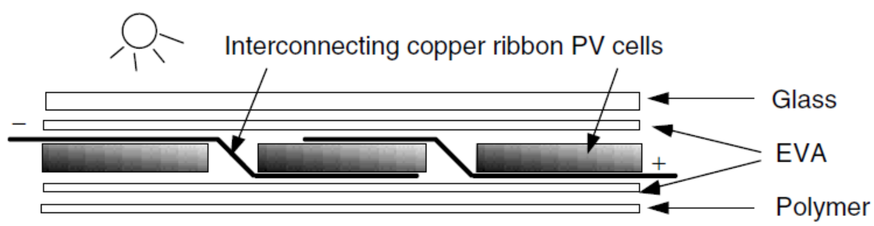


Figure 57. Cystalline PV cell configurations (Masters & Wiley, 2004).

Monocrystalline silicon is often made using the Czochralski process to grow the perfect crystals of silicon. The results are large cylindrical ingots that are then cut into wafers to make PV cells. There is some waste because of this cutting process. Square cells with rounded corners tend to be the optimum shape. The crystalline framework of mono-Si is homogenous, leading to its even-color appearance (Figure 58). Monocrystalline silicon has the highest efficiency in the commercial PV market.

Figure 58. Mono-crystalline solar panel (SunPower, 2011).

Poly- or multicrystalline silicon is made from cast square ingots from the solidification process or continuous ribbon from the silicon melting process. Poly-Si or mc-Si is composed of many small silicon grains of varied crystallographic orientation separated by grain boundaries resulting in the non-uniform appearance of spotted and shiny surfaces (Figure 59). Poly-Si or mc-Si cells are the most popular for PV technology because they are less expensive to produce than monocrystalline silicon; however, they are less efficient.

Figure 59. Polycrystalline solar panels (BP Solar, 2012).

b) Amorphous silicon (a-Si).

Amorphous silicon PV cells are made by depositing extremely thin layers onto a backing material such as glass, stainless steel, or plastic. The p-n junction in a-Si is different from c-Si. Between the p-layer and n-layer, there is an intrinsic or undopted layer (a-Si:H). This structure is called p-i-n (Figure 60).

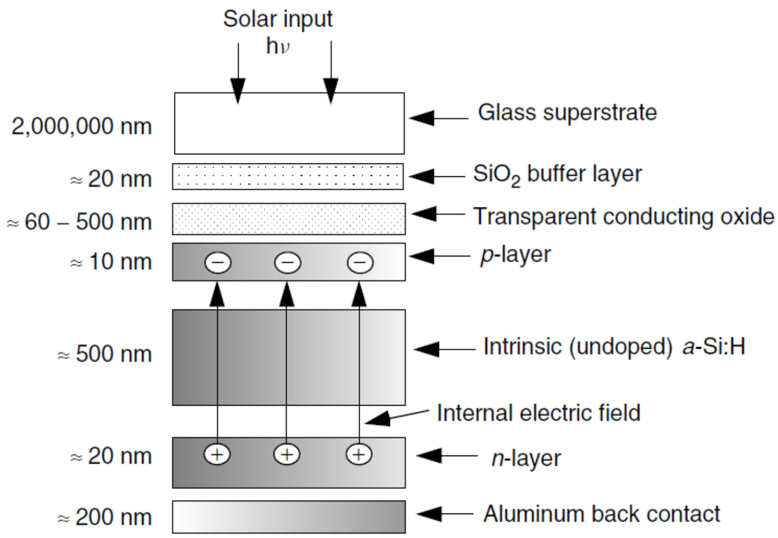


Figure 60. An example of an amorphous silicon p-i-n cell (Masters & Wiley, 2004).

Amorphous silicon cells have lower efficiency compared with crystalline silicon cells. Therefore, they require a larger area to produce the same amount of electricity. The advantages are that they are much cheaper to produce and extremely flexible. The color appearance is uniform (Figure 61).

Figure 61. Amorphous silicon solar panels (Uni-Solar, 2011).

c) Other thin film PV cells.

Even though silicon is dominant in the PV cell industry, there are other types of thin film made from a combination of elements from group III and group

V or elements from group II and group IV or group VI. These groups of elements are those of the periodic table of the chemical elements. Examples of these materials are gallium arsenide and indium phosphate (GaAs and GaInP), cadmium telluride (CdTe), copper indium diselenide (CIS), copper-indium-gallium-diselenide (CIGS). These materials generally have higher efficiency compared with silicon-based materials and are insensitive to heat, making them suitable for concentrated sunlight applications. Some materials such as gallium are rare and production difficulties make them more expensive. These PV cells find their applications in concentrator systems and space programs. On the other hand, CdTe material is a very successful group II-IV compound. Its production is also cheaper than silicon based PV cells, so it has the lowest production cost in PV thin film technology.

Figure 62. CdTe PV cell modules (First Solar, 2012).

d) Multijunction PV cells.

There are at least two multijunction commercial PV cells available. The first one is heterojunction with intrinsic thin layer (HIT) which is composed of crystalline silicon wafers sandwiched between amorphous silicon layers. This combination results in higher PV cell efficiency compared with crystalline silicon, and better performance at higher temperature. The second one is the combination of amorphous silicon and nanocrystalline silicon (a-Si/nc-Si/nc-Si) to expand energy band gaps and increase the efficiency.

e) Emerging materials for PV cells.

Recently, the III-N materials have gained attention as they possess properties suitable for high efficiency PV cells. Among them, indium gallium nitride (InGaN), which is a combination of gallium nitride (GaN) from group III and indium nitride (InN) from group VI, was recently discovered to be able to make use of nearly the entire solar spectrum (0.7 eV – 3.4 eV), making it a promising material for very high efficiency PV cells. The band gap of InN was recently found to be 0.7 eV instead of what was previously believed at 1.3 eV. The band gap of GaN is 3.4 eV. Growing these two elements together, the maximum theoretical efficiencies could be better than 70%. However, the challenge lies in making high enough quality InGaN for PV cells.

f) PV cell efficiencies.

Today, monocrystalline silicon cells and multicrystalline silicon cells have the largest market share. Table 7 compares PV module technologies, characteristics, and their commercially available highest efficiency under the global AM 1.5 spectrum (1000 W/m^2) at 25°C (Green, Emery, Hishikawa, Warta, & Dunlop, 2012) and their commercial module average efficiency (Green, Emery, Hishikawa, Warta, & Dunlop, 2012) and their commercial module average efficiency (EIA, 2009).

Table 7. PV module efficiency, area need and durability.

Materials	**Highest record module efficiency (%)/ Average commercial efficiency (%)**	**Approximate surface area needed for 1 kW DC (m^2)**	**Durability**
Mono-crystalline silicon	22.9± 0.6 / 19	4-5	> 30 years
Poly-crystalline silicon	18.2 ± 0.4 / 14	6-7	> 25 years
Thin film-amorphous silicon	8.2 ± 0.2 / 8	12-13	
CIGS	15.7 ± 0.5 / 12	7-8	> 20 years
CdTe	12.8 ± 0.4 / n/a	8-9	
a-Si/a-SiGe/a-SiGe (tandem)	10.4 ± 0.5 / n/a	9-10	

3.1.4 PV systems.

A typical silicon PV cell produces about 0.6 volt DC when there is no load. This is a very small amount of electric energy. Therefore, the cells are usually connected in series to create more voltage. A PV module usually has 36 to 72 PV cells and is rated between 10-300 kW (Figure 63 and Figure 64).

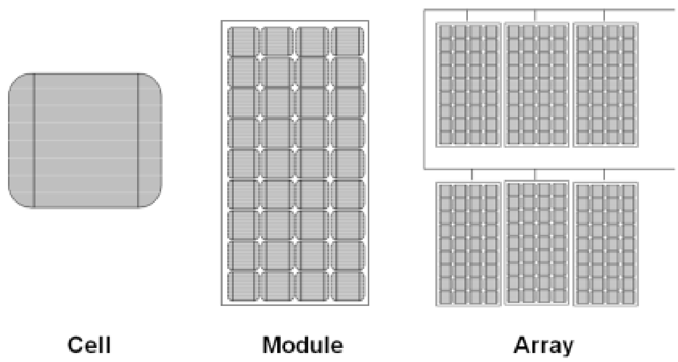


Figure 63. PV cell, module and array (Masters & Wiley, 2004).

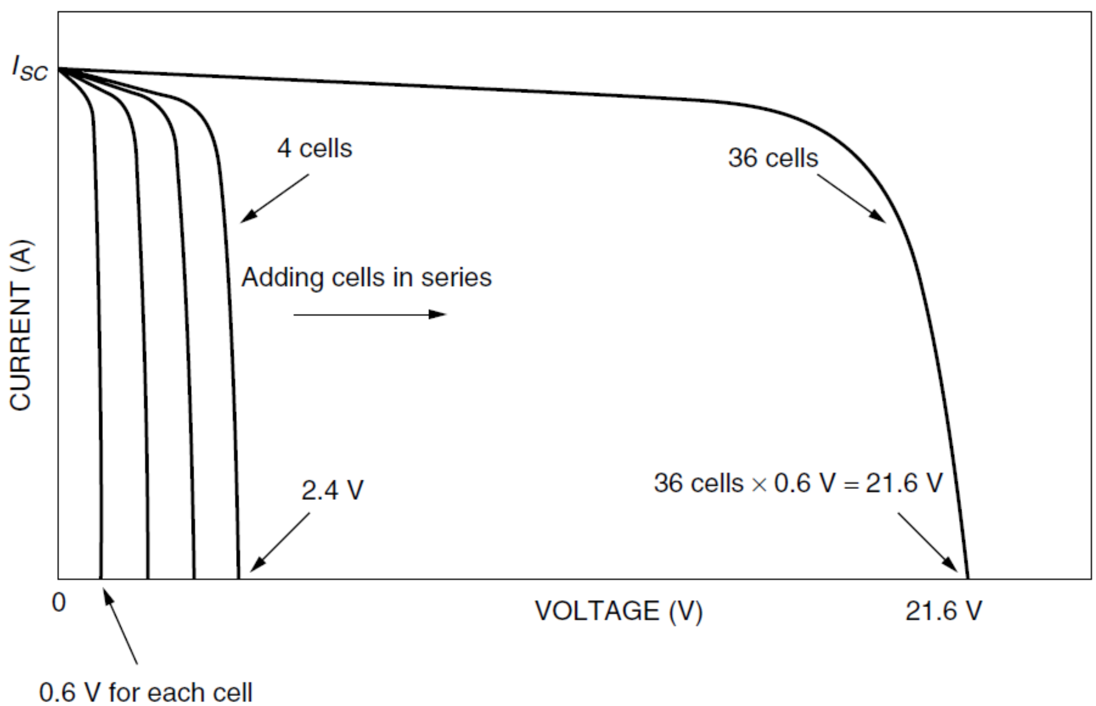


Figure 64. Electric characteristics when cells are connected together in series within a module (Masters & Wiley, 2004).

Crystalline silicon modules consist of individual PV cells connected together and encapsulated between a transparent front, usually glass, and a backing material that is usually plastic or glass. Thin film modules are constructed from single sheets of thin film material and can be encapsulated in the form of a flexible or fixed module, with transparent plastic or glass as front material. PV modules are typically guaranteed for 5 to 10 years by the manufacturers. The power output warranty is typically between 20 to 25 years with minimal drop.

When modules are connected in series (or string), currents will stay the same, but voltage increases. On the other hand, when modules are connected in parallel, the current increases, and voltage stays the same (Figure 65 and Figure 66). The parallel circuit is preferred if there are shading problems. With parallel circuits, when there are shading problems in some parts of the arrays, the voltage can still be kept at the same level with only current drop occurring.

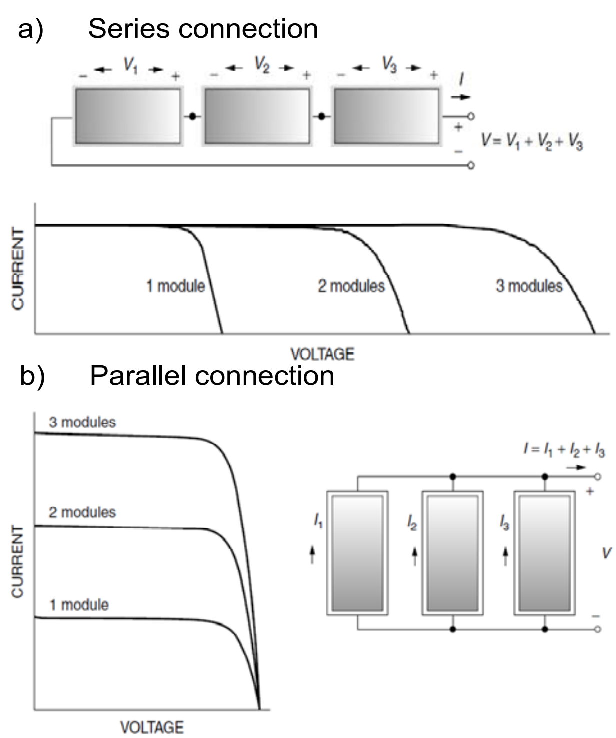


Figure 65. PV voltage and current characteristics when connected together in series or parallels.

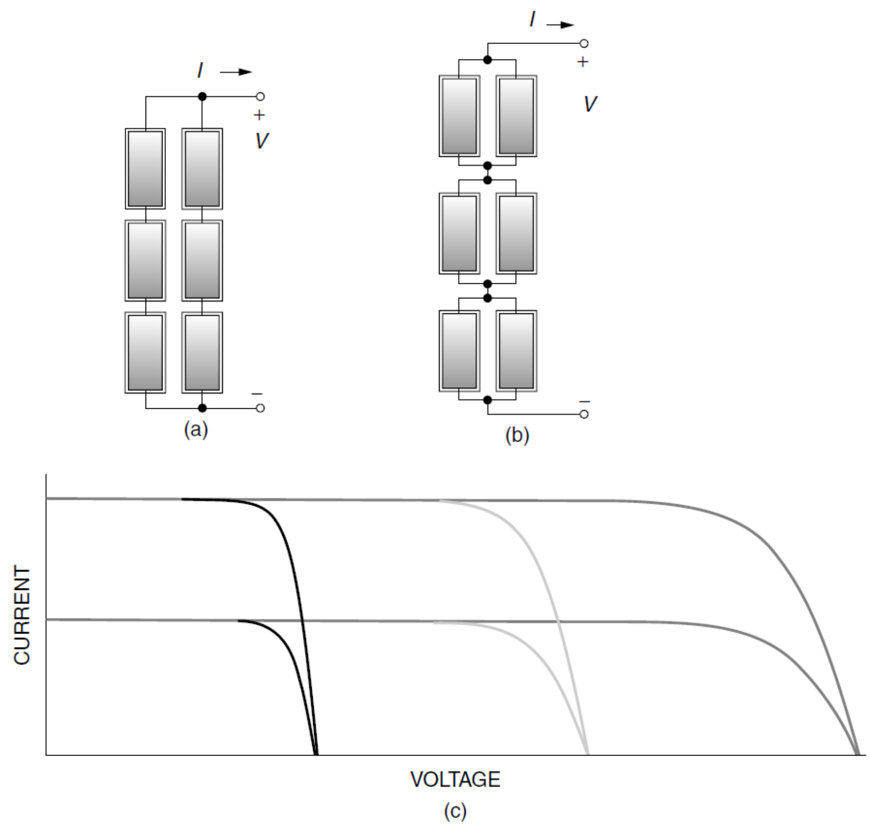


Figure 66. The increase of voltage and current in a PV array when connected together in series and parallels (Masters & Wiley, 2004).

The current is directly proportional to the intensity of sunlight striking the surface of the cell. However, the voltage can be influenced by panel surface temperature because high temperature reduces panel efficiency. For crystalline silicon technology, higher temperature has a negative impact on the voltage. At temperatures above 25°C, the module power will decrease 0.4-0.5% with every 1°C temperature increase (Figure 67). Arrays with enough ventilation will result in higher power output. Thin film technology is less sensitive to the temperature. When temperatures go higher, the thin film module's output will decrease 0.1-0.2% with every 1°C temperature increase.

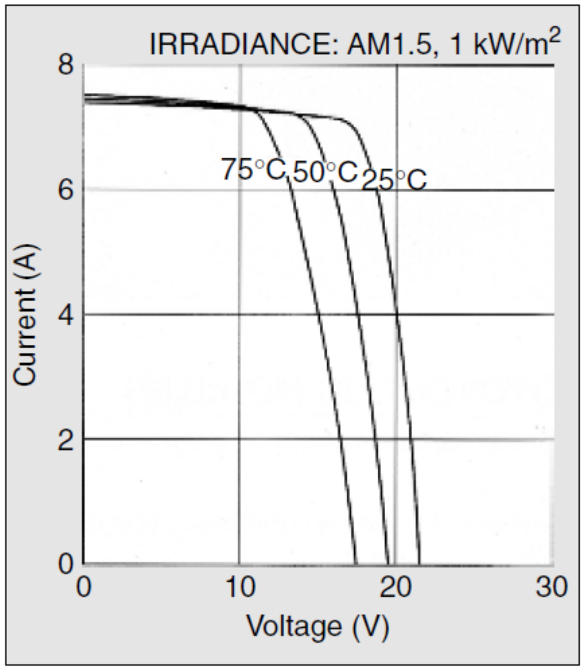


Figure 67. PV efficiency reduces with higher module surface temperature (Masters & Wiley, 2004).

The PV cell is very sensitive to shading. Shading analysis from nearby obstructions is among the first tasks to perform when considering a PV project. Unlike solar thermal panels used for hot water production that can tolerate shadings, many technologies of PV modules cannot even be shaded by the branch of a leafless tree. Because all cells are connected in series, when one cell's performance drops because of shading from tree branches, dust, or nearby structures, it can have a substantial negative impact on overall energy production that is more than proportional to its area (Vignola, 2007; Woyte, Nijs, & Belmans, 2003). Typically, in urban area, the rooftop is the best place that is mostly free from shadings. A ground mounted system is not favorable because of the uncertainty of nearby areas which are out of control.

In some cases, shadings are hard to avoid. Other problems such as mismatch and soiling also cause PV electricity output to drop. To mitigate this problem, PV modules normally have three to four bypass diodes installed. Too few bypass diodes cannot mitigate the shading effect very well. Too many bypass diodes consume voltage from the module itself (Ubisse & Sebitosi, 2009). Another solution is to install a micro-inverter in every module instead of one inverter for the system. This increases efficiency and reliability, as well as flexibility of PV design. However, installing micro-inverters also increases the total system cost.

A PV array can be installed as fixed tilt systems, one-axis tracking systems, or two-axis tracking systems. Tracking systems can increase electricity output by about 30% compared with a fixed tilt system (Figure 68). However, the structure of the system will become more complex and more expensive. Tracking systems are suitable for ground-mount and large scale projects.

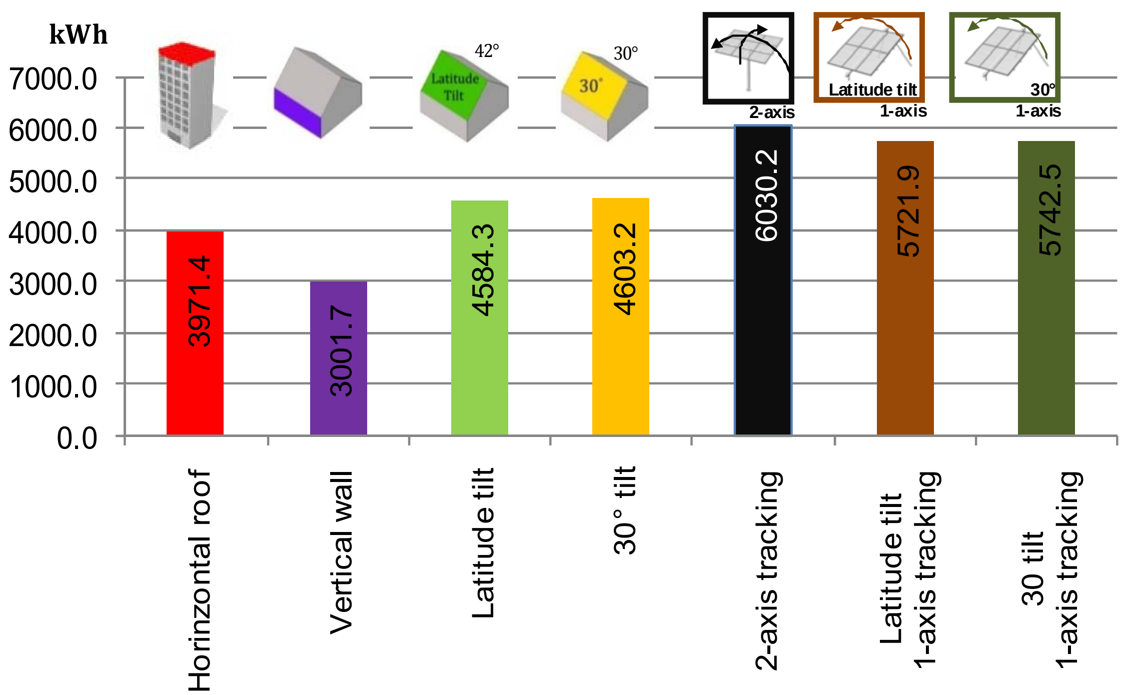


Figure 68. PV electricity annual output from a 4 kW DC system in Detroit, MI.

Optimum angle for installing a PV module is a latitude tilt angle of the location ± 15°. The best orientation is facing south for a building located in the northern hemisphere and facing north for building located in the southern hemisphere. Figure 69 shows daily average solar insolation in each month on a 4KW DC system installed at different tilt angles in Detroit, which is located at latitude N 42.2°. The highest solar insolation comes from a system placed horizontally with a tracking system. Without tracking systems, systems with tilt angle between 20°-40° receive the highest solar insolation.

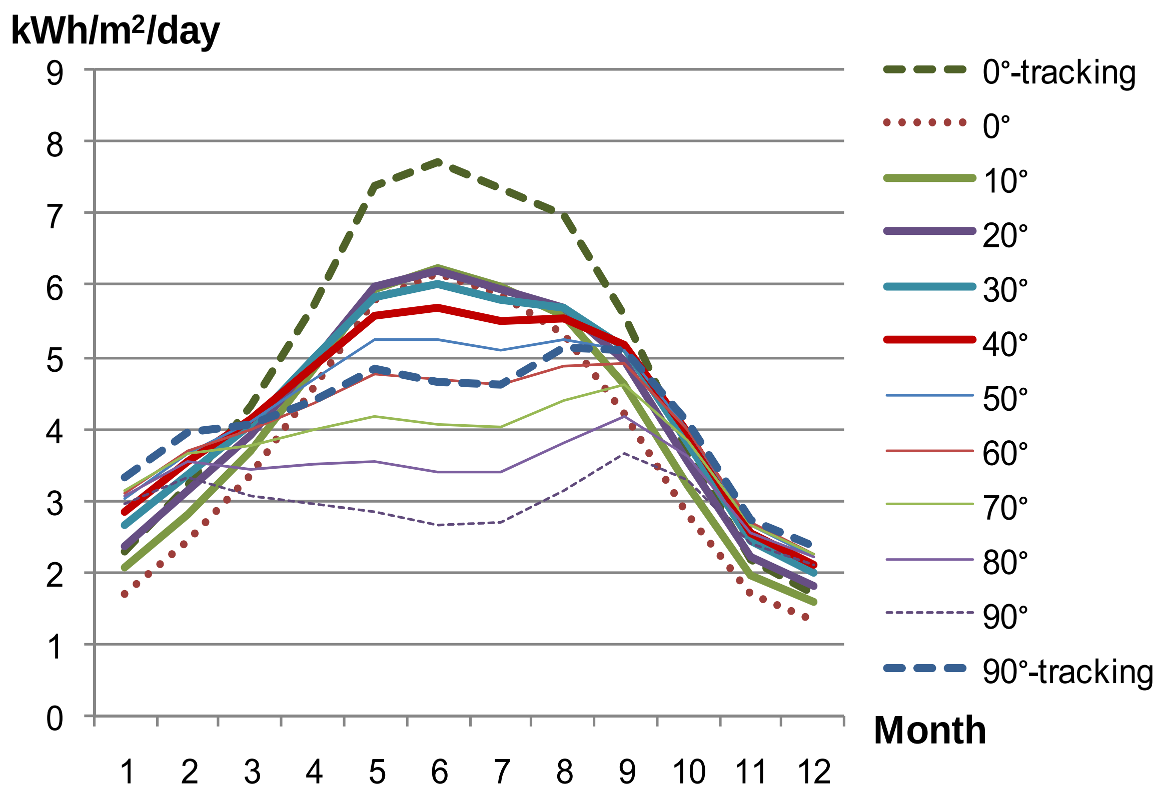


Figure 69. Daily average solar insolation on a 4 kW DC PV system installed at various tilt angles in Detroit, MI.

Figure 70 shows solar insolation falling onto a 4kW DC system in Detroit, MI, in relation to its orientation when placed at a 30° tilt angle. In this particular climate, placing PV panels facing north can reduce the amount of solar insolation by approximately 38%. Placing the system facing east or west can reduce the amount of solar insolation from 16%-19% compared with the same system at a 30° tilt angle facing southern orientation.

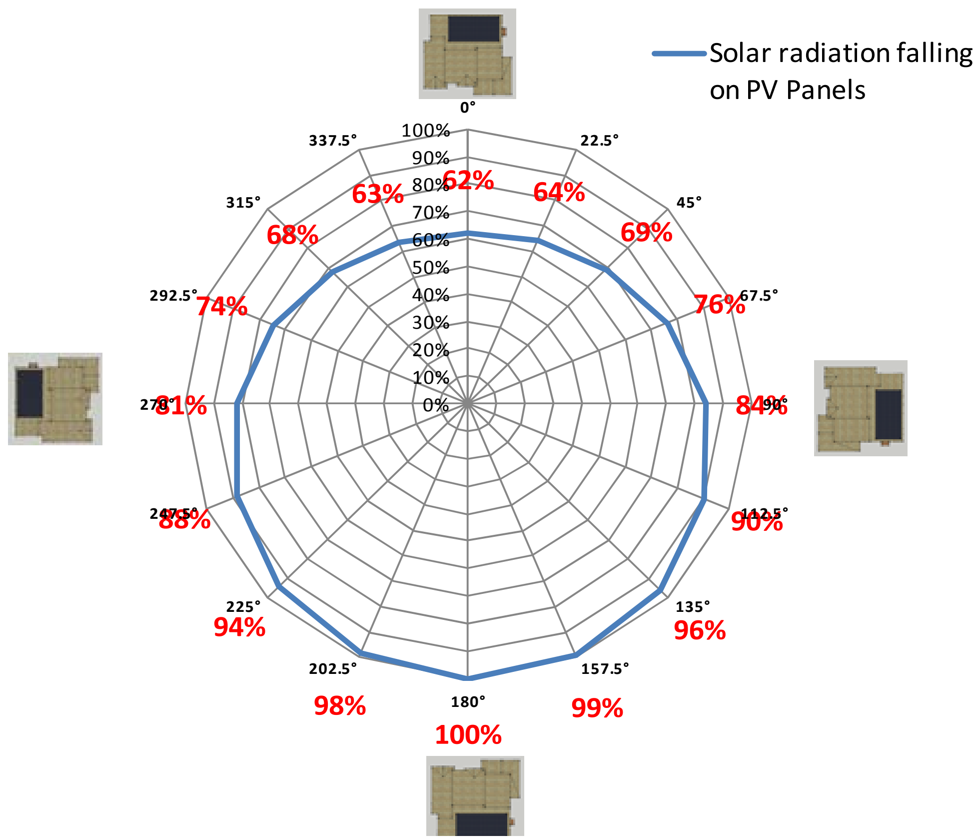


Figure 70. Solar insolation falling onto a 4 kW DC PV system installed at a 30° tilt angle compared with the same system facing southern orientation in Detroit.

In urban locations where there is limited rooftop area, the building façade is another good candidate for PV application. However, solar radiation falling onto a vertical façade is normally less than tilted surfaces or horizontal surfaces of the same size. For example, the previous graph shown in Figure 68 shows that the system placed vertically produced 30% less electricity than the same system placed with 30° tilt angle. The exception to this is at very high latitude locations such as Alaska, where solar radiation falling on a vertical façade is more than the horizontal surface. Figure 71 shows possible ways to apply a PV system on a high-rise residential building façade.

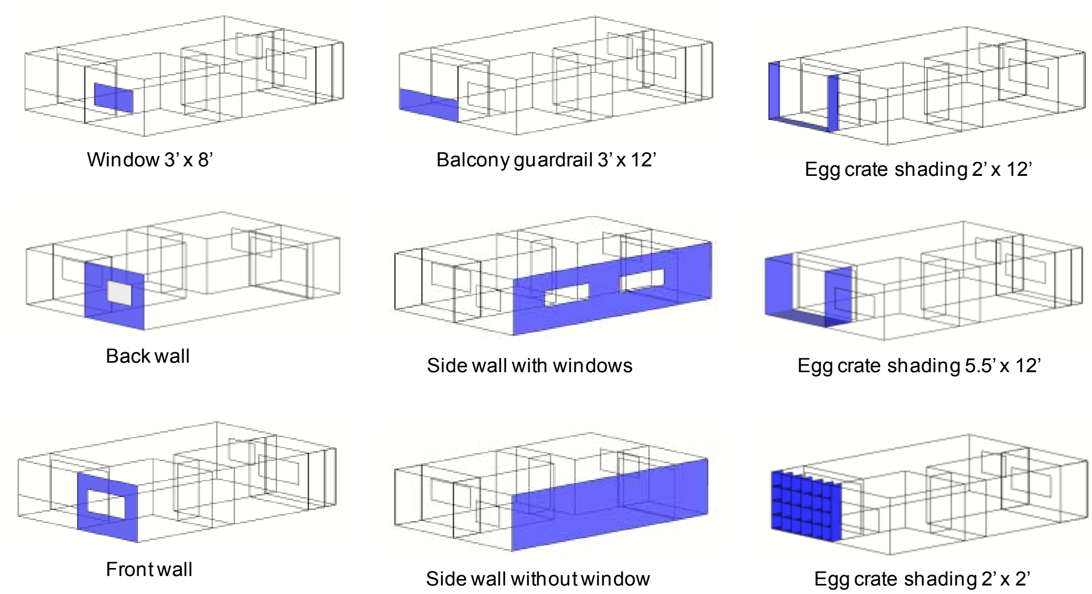


Figure 71. Possible locations for PV systems on building façades.

PV systems can be installed over an existing roof. Even though the system weight is generally light, inspection of the roof structure by structural engineers is recommended before installation. Periodic examination and cleaning should be scheduled as routine preventive maintenance. Therefore, maintenance should be planned when locating the system. Dust, bird drops, or snow can significantly reduce the system output if left on the arrays.

In grid-connected PV systems, electricity output from the PV systems can be sent to the electric grids when it is not used. Buildings can also use electricity from the electric grids when the PV system cannot provide enough electricity. Energy storage can also be used to store excess electricity. In order to send electricity from a PV system to the electric grid, there are two approaches that have been implemented. The first one is called net metering, where customers pay a utility bill for the difference between electricity used from the electric grid and the amount of electricity sent back to the electric grid. The second approach is called feed-in tariffs, where the utility buys PV electricity from customers under a multiyear contract at a guaranteed rate, usually a lot higher than conventional electrical cost.

The primary component in grid-connected PV systems is the inverter to convert DC to AC and regulate the PV system electricity when connected to the utility grids. Overall, the grid-connected PV system is comprised of PV panels, combiner box, inverter, main breaker panel, two-way electrical meter, and household loads (Figure 72).

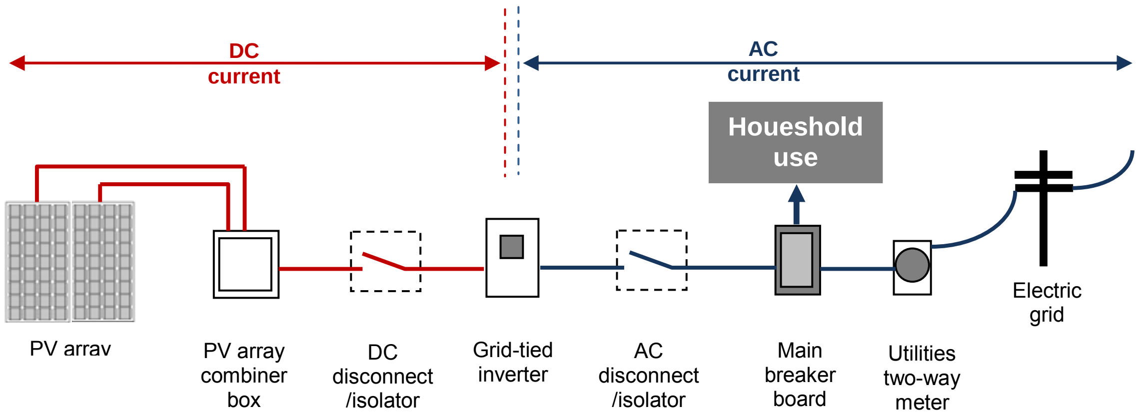


Figure 72. Detailed grid-connected PV system diagram.

3.1.5 PV simulation software.

Some building simulation software packages have basic PV calculation modules. For example, eQUEST has Sandia models and Kings models. EnergyPlus® has simple equivalent one-diode or Sandia models to predict electrical production from a PV module (B. T. Griffith & Ellis, 2004). However, an inverter model and other system components were not available. Using these software packages, PV systems were assumed to operate at ideal conditions. For this reason, PV electricity output was calculated using a separate program called System Advisor Model (SAM). SAM is a stand-alone renewable energy system performance and economics simulation program. It is available for free. This tool was developed by the NREL in collaboration with Sandia National Laboratories and in partnership with the Solar Energy Technologies Program (SETP), and the U.S. DOE. The full version was first available in 2006. It reads weather data files in three formats: TMY2, TMY3, and EPW. All detailed information as well as shading data from other simulation programs can be fed into the program. The program is well validated against measurement data (Fanney et al., 2006; Fanney, Dougherty, & Davis, 2009).

For PV system performance, SAM can model a range of solar energy technologies including crystalline silicon (cSi), thin film (CdTe, CiS, and aSi) concentration photovoltaic (CPV), multijunction concentrator photovoltaic (mj-CPV) and heterojunction with intrinsic thin layer (HIT). Within SAM, there are options of sub simulation models to choose from (Figure 73). Plane of array (POA) solar radiation models available in SAM are isotropic sky (Liu & Jordan, 1963), Hay and Davies (Hay & Davies, 1980), Reindl (Reindl, 1988) and Perez (Perez et al., 1990; Perez et al., 1988). Array performance models, implemented using the TRNSYS program (Beckman et al., 1994) as a simulation engine, are Sandia model (King, Boyson, & Kratochvil, 2004), CEC performance model (De Soto, 2004), simple efficiency model and concentrating PV model. The result from an array performance model is direct current (DC) electricity output produced from PV arrays. There are two inverter models available. They are the Sandia model (King et al., 2007) and the single-point efficiency model. The result from inverter model simulation is alternate current (AC) electricity output that an inverter converts from DC output.

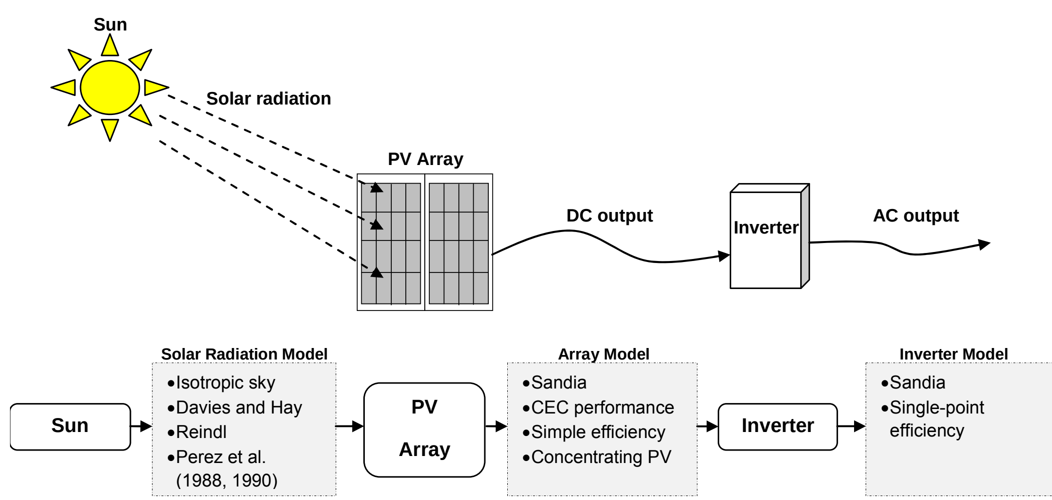


Figure 73. Diagram of mathematic models available in SAM.

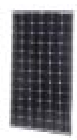
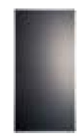
The models selected in this study are the Perez 1990 solar radiation model, the Sandia array model, and the Sandia inverter model. The Perez 1990 model is the update of the Perez 1988 model and is widely used in simulation programs to calculate solar irradiance falling onto tilted surfaces. With the global horizontal and direct normal irradiance data from weather data sets, total solar irradiance falling on a tilted surface can be computed. When compared with other models, the Perez model gives the best estimate global solar radiation on a tilted surface, especially on clear sky days (Gueymard, 2009). Loutzenhiser et al. validated radiation models against measured data in March and April in Switzerland. There were seven models in the evaluation including the 5 models available in SAM. The results show that Perez 1990 yielded the best result by producing the smallest mean absolute different number (Loutzenhiser et al., 2007). Another work done to evaluate 12 transposition models using Iran's radiation measured data also showed that the 1990 Perez model gave the best overall estimation of total radiation falling onto tilted surfaces (Noorian, Moradi, & Kamali, 2008).

The Sandia PV Array Performance model and the Sandia Inverter Performance model use theoretical and semi-empirical methods. They utilize databases of empirically derived parameters developed by testing commercial PV modules and inverters in actual conditions. The validation of the Sandia PV Array Performance model was done by Fanney et al. (Fanney et al., 2009) and found to be accurate within 1-8% of the measurement data, except for the tandem-junction amorphous silicon modules because of their energy output degradation characteristics (Fanney et al., 2009). In another study, the prediction accuracy of the Sandia PV Array Performance model was found to be generally within 5% (Cameron, Boyson, & Riley, 2008). In the same study, the Sandia Inverter Performance model accuracy was found to be within 1% of measured performance.

3.1.6 PV system modeling in baseline buildings.

Five PV technologies were selected for the initial simulation and their electricity outputs were used in the study. Their actual performances, except for InGaN, were used as inputs. Their properties are summarized in Table 8.

Table 8. Characteristics of selected PV modules used in simulations.

Brand	Uni-Solar PVL-144 	Sanyo HIT N,A 	SunPower 210 	First Solar FS 270 	Future PV
STC rated power (W)	144	210	210	70	n/a
Cell technology	Triple Junction a-Si	mono-Si+a-Si	mono-Si	CdTe	InGaN
Diode	Across every cell	3	3	none	n/a
Cover	EFTE	Laminated glass	High transmission tempered glass	laminated glass	n/a
Weight	7.7 kg	16 kg	15 kg	12 kg	n/a
Size	5.5 m x 0.4 m	0.8 m x 1.6 m	0.8 m x 1.6 m	0.6 m x 1.1 m	0.8 m x 1.6 m
Area needed for 1 kW DC System (m^2)	15.0	6.0	5.9	9.2	2.0
Voltage at P_{max} (V)	33	41.3	40	65.5	n/a
Current at P_{max}(A)	4.36	5.09	5.25	1.07	n/a
Open-circuit voltage (V_{oc})	46.2	50.9	47.7	88	n/a
Short circuit current(I_{sc})	5.3	5.57	5.75	1.23	n/a
Module efficiency	6.7%	16.7%	16.9%	10.9%	50%
Warranty	5 years Power Output: 92% at 10 years 84% at 20 years 80% at 25 years	5 years Power Output: 90% at 10 years 80% at 20 years	10 years Power Output: 90% at 12 years 80% at 25 years	5 years Power Output: 90% at 10 years 80% at 25 years	n/a n/a

In this study, inverter models are the SMA with size varied between 4,000-8,000 kW depending on PV array sizes. AC derate factors from various variables according to PVWATTS are shown in Table 9. Derate factors for the Sandia array model are efficiency reduction because of mismatch loss, wiring, diodes and connections, soiling, and module degradation. Derate factors for the Sandia inverter model are from wiring and transformer.

Table 9. AC derate factors (NREL, 2012a).

Component Derate Factors	Component Derate Value
PV module nameplate DC rating	0.95
Inverter and Transformer	0.92
Mismatch	0.98
Diodes and connections	0.995
DC wiring	0.98
AC wiring	0.99
Soiling	0.95
System availability	0.98
Shading	1
Sun-tracking	1
Age	1
Overall DC to AC derate factor	**0.77**

When grid-connected, the PV system does not have to satisfy the overall electricity load demand of the building like those in a stand-alone system. The size of the system can depend on the available installed area and the available budget. It can also depend on building owner goals in installing the PV system, such as to generate a certain portion of the building's load, to be self-sufficient, to maximize benefit with feed-in tariff, to maximize the incentive amount, or to be able to expand in the future. The output of a PV system depends on its size, solar availability, system placement, and inverter performance.

Utility policies might also post the limit to PV system size. For example, preventing excess electricity to be sold to the electric grid by limiting the annual electricity output from a PV system that can be sold back to the electric grid must not exceed the building's annual energy consumption. This type of policy would result in building owners trying to install the system size that can generate electricity not exceeding the building's demand. A grid-connected PV system's benefit can be increased with an energy storage system. Without energy storage, when the electric grid is out, the PV system must be shut down because of safety reasons, no matter if the sun is still shining. The system could not be used for outage prevention or outage recovery. However, energy storage also increases the cost of the entire system.

In this study, PV arrays are assumed to be placed on building rooftops. There are gable rooftops on residential buildings as well as small commercial buildings and industrial buildings. Half of the gable roof area is tilted toward the northern orientation, which is not suitable for PV installation. These buildings will have a PV system no larger than the half of the roof area that is tilted toward the southern orientation (Figure 74).

From the building area and function, parking space can be approximately calculated. Medium commercial buildings need 150 parking spaces; big commercial buildings need 1,500 parking spaces. Industrial buildings, even though they are larger areas, require less usable parking space per building than office buildings. Consequently, 166 parking spaces are required for the industrial cases. Assume that the medium commercial buildings and industrial buildings both have ground parking space and among them, 45 parking spaces are covered, the cover structure dimension would be 120 m x 5.5 m. Assume that a big commercial building has a parking structure for 1,500 cars. The parking structure would be 6 stories with the same dimension as the big commercial building at 50 m x 70 m. These parking spaces add more opportunities to apply PV systems onto their roofs if the investment is possible.

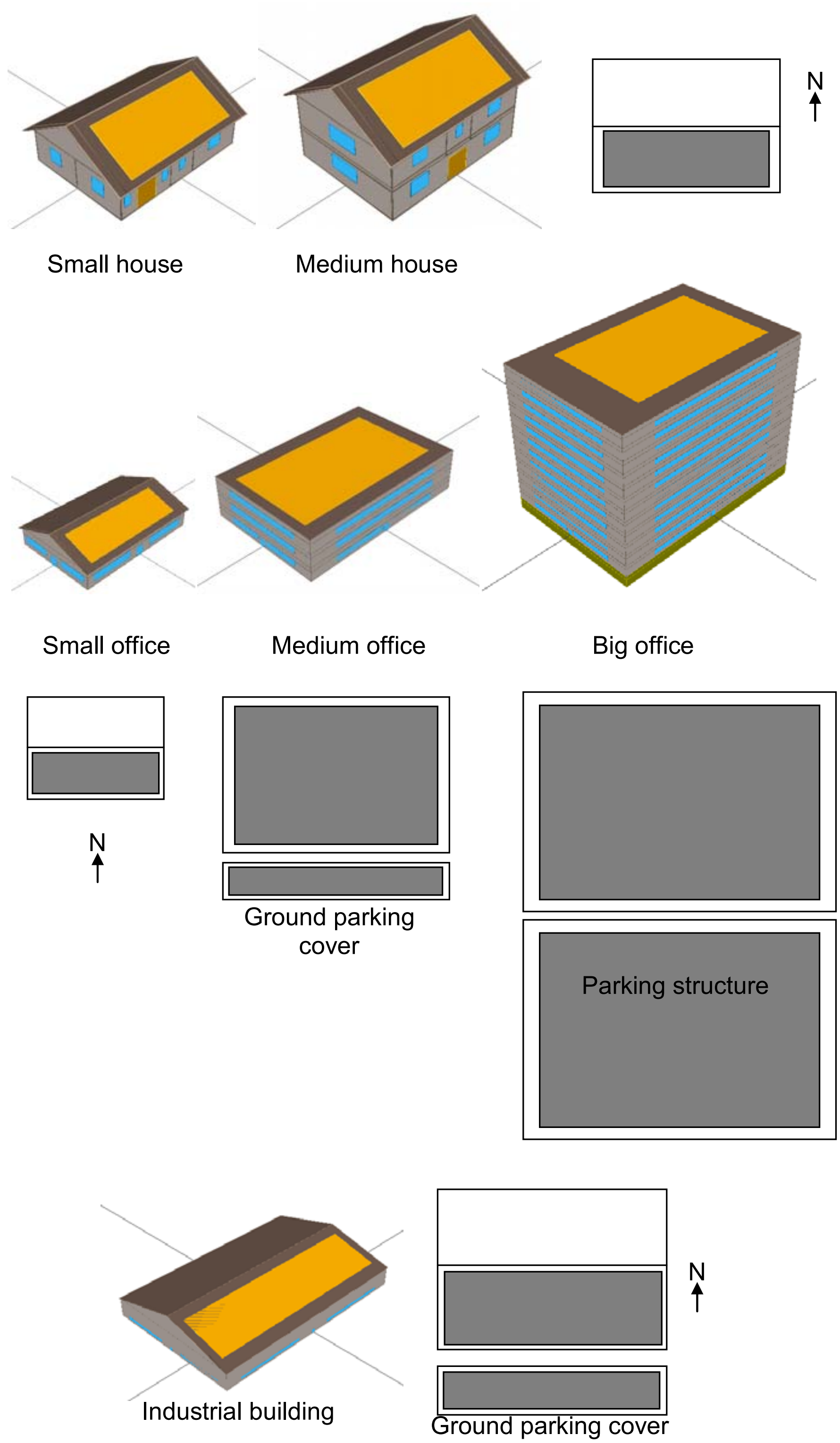


Figure 74. Locations of PV system installations.

With the dimensions of PV panels indicated in Table 8, PV system size can be calculated (Table 10). Typical sizes of PV systems in each building type were selected from literature.

Table 10. PV size use in the simulations for each building type.

Building type	PV size	SunPower & HIT	FirstSolar	Uni-Solar
Small/medium house Roof area: 5.8 m x 13.4 m (half roof) Typical PV size : 4 kW	**Typical size**	20 panels 4.21 kW	56 panels 4.48 kW	33 panels 4.5 kW
	Fit roof	48 panels 10.08 kW	84 panels 5.88 kW	33 panels 4.5 kW
Small office Roof area: 11.7 m x 32 m (half roof) Typical PV size : 20 kW	**Typical size**	96 panels 20.16 kW	290 panels 20.30 kW	150 panels 20.40 kW
	Fit roof	240 panels 50.4 kW	500 panels 35 kW	150 panels 20.40 kW
Medium office Roof area: 33.5 m x 49.5 m Typical PV size : 30 kW Parking roof: 5.5 m x 120 m	**Typical size**	140 panels 29.4 kW	420 panels 29.4 kW	225 panels 30.6 kW
	Fit roof	800 panels 168 kW	1680 panels 117.6 kW	500 panels 68 kW
	Parking roof	270 panels 56.7 kW	480 panels 33.6 kW	180 panels 24.48 kW
Big office Roof area: 47 m x 70 m Typical PV size : 100 kW Parking structure roof area: 47 m x 70 m	**Typical size**	480 panels 100.8 kW	1500 panels 105 kW	750 panels 102 kW
	Fit roof	1632 panels 342.7 kW	3200 panels 224 kW	960 panels 130.6 kW
	Parking roof	1632 panels 342.7 kW	3200 panels 224 kW	960 panels 130.6 kW
Industrial building Roof area: 43 m x 132 m (half roof) Typical PV size : 500 kW Parking roof: 5.5 m x 120 m	**Typical size**	2500 panels 503 kW	7200 panels 504 kW	2760 panels 375 kW
	Fit roof	4800 panels 1008 kW	9000 panels 630 kW	2760 panels 375 kW
	Parking roof	270 panels 56.7 kW	480 panels 33.6 kW	180 panels 24.48 kW

Electricity outputs from PV systems installed on these buildings are indicated in Figure 75 and Figure 76. Residential buildings can accommodate small PV systems, however, the number of buildings can increase the PV size when connected to each other as a community or even a town via the electric grids. Commercial and industrial buildings have large roof areas that can accommodate PV systems. The system high investment tends to limit project size on these buildings.

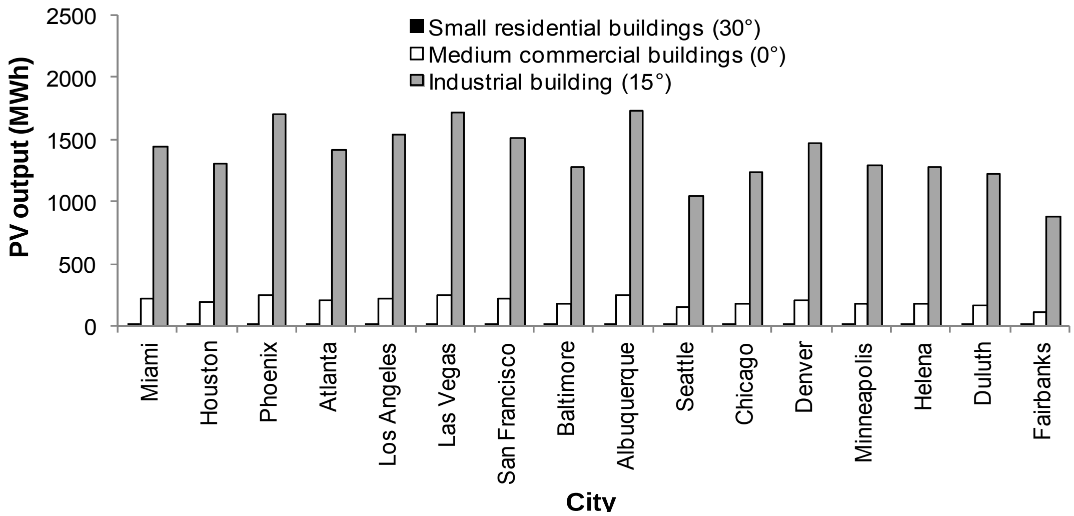


Figure 75. Examples of PV annual electricity output from SAM using SunPower PV panel characteristics when installed on residential, commercial, and industrial buildings located in 16 cities if all available roof areas are used.

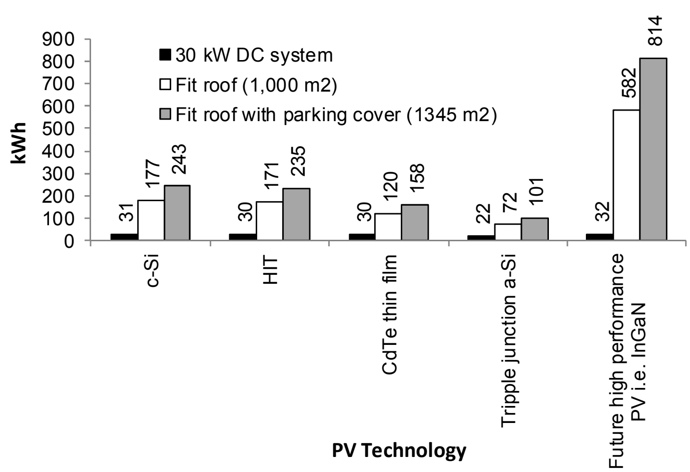


Figure 76. PV electricity output generated from different PV technologies and different areas available at a medium commercial building in Chicago.

3.2 Energy Efficiency Design Strategies Priorities in Buildings with Grid-Connected PV Systems

Energy efficiency design strategy potential is presented in section 2.4.4 using annual energy consumption, annual electricity consumption, and July's peak electricity demand data of buildings in Miami and Chicago. Data from buildings with 24-hour use in Chicago are also presented. In this section, these strategies are further discussed and prioritized by looking at annual electricity consumption and annual peak electricity demand. Best strategies are plotted against existing and ASHRAE compliant building results, as well as electricity output from SunPower PV systems of typical size and full-roof area covered size. Results from six cities representing six climate zones are presented. They are Miami (Zone 1A), Phoenix (Zone 2B), Las Vegas (Zone 3B), Baltimore (Zone 4A), Chicago (Zone 5A), and Duluth (Zone 7).

3.2.1 Annual electricity reduction.

Residential buildings: Results from small houses demonstrated that reducing lighting power density was the most effective single strategy in reducing annual electricity consumption. Using high efficiency appliances came second or third, depending on climate zones. Other strategies that came second or third in reducing residential building annual energy consumption were setting thermostat 1.1°C (2°F) higher in summer and 1.1°C (2°F) lower in winter (Miami, Baltimore, and Chicago), insulation level increased in wall, roof, and glazing (Phoenix and Las Vegas), and daylighting (Duluth). For a combination of strategies, ZEB – which included almost all single strategies – can reduce annual electricity use at a level that enables electricity output from a typical 4 KW DC size PV system to satisfy the remaining electricity demand for small houses in all cities. Data of annual electricity consumption when each energy efficiency design strategy was applied to small houses, including the percentage of consumption compared with existing buildings in six cities, can be found in Table 11. Table 12 shows the results of medium houses, in which lighting power density is also the best single strategy in reducing annual electricity consumption, followed by using high efficiency appliances. Electricity use in residential buildings decreases as the climate gets colder, because the heating requirement increases and the main energy source is natural gas.

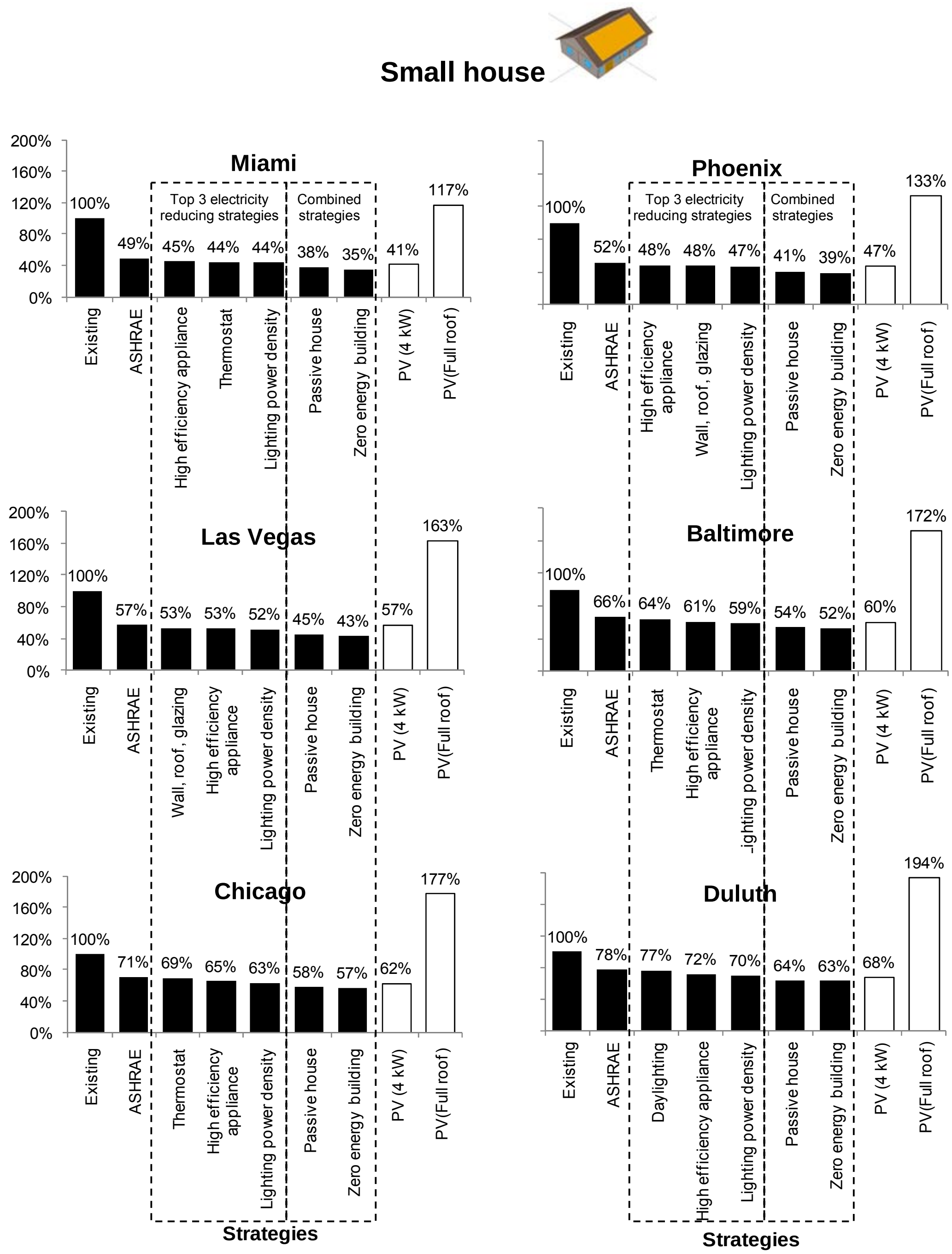
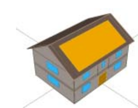


Figure 77. Top five annual electricity consumption reducing strategies compared with electricity consumption in existing and ASHRAE compliant buildings and electricity output from PV systems in small houses located in six cities.

Table 11. Annual electricity consumption in small houses when energy efficiency design strategies were applied in six cities.

Strategies	Miami		Phoenix		Las Vegas		Baltimore		Chicago		Duluth	
	kWh	%	kWh	%	kWh	%	kWh	%	kWh	%	kWh	%
Existing	11.85	100%	12.70	100%	10.57	100%	7.44	100%	6.94	100%	6.47	100%
ASHRAE	5.81	49%	6.59	52%	6.03	57%	4.93	66%	4.92	71%	5.04	78%
Wall insulation	5.58	47%	6.20	49%	5.76	54%	4.89	66%	4.88	70%	5.04	78%
Roof insulation	5.77	49%	6.56	52%	6.01	57%	4.92	66%	4.92	71%	5.04	78%
Glazing	5.73	48%	6.49	51%	5.91	56%	4.87	65%	4.88	70%	5.03	78%
Wall, roof, glazing	5.45	46%	6.05	48%	5.61	53%	4.82	65%	4.84	70%	5.03	78%
Daylighting	5.78	49%	6.56	52%	5.95	56%	4.86	65%	4.86	70%	4.97	77%
Thermal Mass	5.97	50%	6.64	52%	6.11	58%	4.91	66%	4.90	71%	5.04	78%
Cooling	5.60	47%	6.33	50%	5.85	55%	4.88	66%	4.90	71%	5.04	78%
Heating	5.81	49%	6.59	52%	6.03	57%	4.93	66%	4.92	71%	5.04	78%
Lighting power density	**5.20**	44%	**6.00**	47%	**5.47**	52%	**4.38**	59%	**4.39**	63%	**4.52**	70%
High efficiency appliance	5.35	45%	6.15	48%	5.60	53%	4.52	61%	4.52	65%	4.64	72%
Thermostat	5.24	44%	6.24	49%	5.76	55%	4.78	64%	4.81	69%	4.98	77%
Passive house	**4.50**	38%	**5.19**	41%	**4.77**	45%	**3.99**	54%	**4.01**	58%	**4.12**	64%
Zero energy building	**4.14**	35%	**4.98**	39%	**4.56**	43%	**3.89**	52%	**3.92**	57%	**4.08**	63%

Table 12. Annual electricity consumption in medium houses when energy efficiency design strategies were applied in six cities.



Strategies	Miami		Phoenix		Las Vegas		Baltimore		Chicago		Duluth	
	kWh	%	kWh	%	kWh	%	kWh	%	kWh	%	kWh	%
Existing	21.37	100%	23.25	100%	19.78	100%	14.46	100%	13.46	100%	12.30	100%
ASHRAE	10.83	51%	11.98	52%	11.18	57%	9.43	65%	9.38	70%	9.31	76%
Wall insulation	10.75	50%	11.37	49%	10.80	55%	9.40	65%	9.34	69%	9.30	76%
Roof insulation	10.80	51%	11.96	51%	11.15	56%	9.42	65%	9.39	70%	9.31	76%
Glazing	10.70	50%	11.76	51%	10.85	55%	9.27	64%	9.25	69%	9.24	75%
Wall, roof, glazing	10.48	49%	11.06	48%	10.36	52%	9.21	64%	9.19	68%	9.23	75%
Daylighting	10.74	50%	11.85	51%	11.00	56%	9.29	64%	9.25	69%	9.17	75%
Thermal Mass	11.14	52%	12.03	52%	11.20	57%	9.20	64%	9.16	68%	9.27	75%
Cooling	10.51	49%	11.57	50%	10.87	55%	9.33	65%	9.31	69%	9.29	76%
Heating	10.83	51%	11.98	52%	11.18	57%	9.43	65%	9.38	70%	9.31	76%
LPD	**9.62**	45%	**10.80**	46%	**10.03**	51%	**8.31**	57%	**8.28**	62%	**8.24**	67%
High efficiency appliance	9.92	46%	11.09	48%	10.31	52%	8.59	59%	8.55	64%	8.50	69%
Thermostat	10.03	47%	11.49	49%	10.78	55%	9.19	64%	9.18	68%	9.21	75%
Passive house	**8.28**	39%	**9.18**	39%	**8.56**	43%	**7.40**	51%	**7.42**	55%	**7.46**	61%
Zero energy building	**8.09**	38%	**8.78**	38%	**8.20**	41%	**7.14**	49%	**7.17**	53%	**7.32**	60%

Commercial buildings: Results from medium office buildings show that using high efficiency appliances was the most effective single strategy in reducing annual electricity consumption. Reduced lighting power density was the second most effective strategy in hot and mild climates, while daylighting was second in cold climates. For a combination of strategies, ZEB can reduce annual electricity at around 30% from existing buildings (Figure 78).

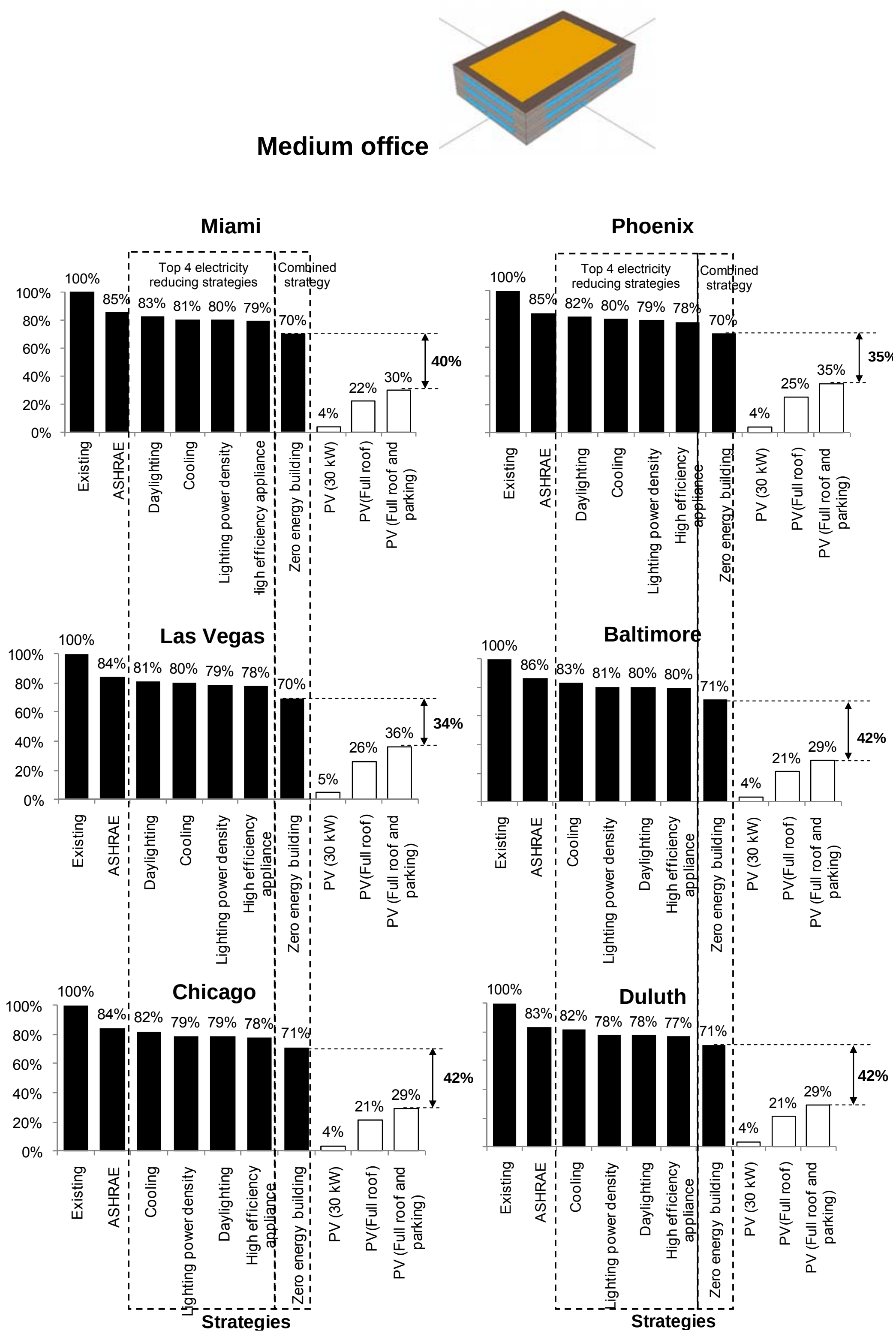
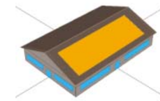


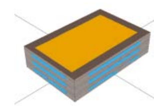
Figure 78. Top five annual electricity consumption reducing strategies compared with electricity consumption in existing and ASHRAE compliant buildings and electricity output from PV systems in medium office buildings located in six cities.

Table 13. Annual electricity consumption in small offices when energy efficiency design strategies were applied in six cities.



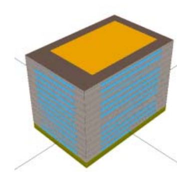
Strategies	Miami		Phoenix		Las Vegas		Baltimore		Chicago		Duluth	
	kWh	%	kWh	%	kWh	%	kWh	%	kWh	%	kWh	%
Existing	56.99	100%	60.70	100%	56.92	100%	45.82	100%	44.35	100%	42.90	100%
ASHRAE	46.62	82%	47.24	78%	43.43	76%	39.69	87%	37.12	84%	34.94	81%
Wall insulation	46.37	81%	46.88	77%	43.07	76%	39.67	87%	37.05	84%	34.88	81%
Roof insulation	46.60	82%	47.21	78%	43.40	76%	39.68	87%	37.11	84%	34.94	81%
Glazing	46.57	82%	47.46	78%	43.71	77%	38.23	83%	36.39	82%	33.80	79%
Wall, roof, glazing	46.08	81%	46.69	77%	43.17	76%	37.99	83%	36.30	82%	33.73	79%
Daylighting	**40.73**	71%	**41.36**	68%	**37.78**	66%	**31.02**	68%	**29.08**	66%	**27.45**	64%
Thermal mass	45.23	79%	46.43	76%	42.62	75%	38.88	85%	36.48	82%	34.31	80%
Cooling	42.76	75%	43.42	72%	40.62	71%	37.90	83%	35.98	81%	34.52	80%
Heating	46.62	82%	47.24	78%	43.43	76%	39.69	87%	37.12	84%	34.94	81%
Thermostat setting	45.09	79%	45.96	76%	42.51	75%	38.74	85%	36.62	83%	34.69	81%
High efficiency appliance	43.62	77%	44.27	73%	40.60	71%	36.87	80%	34.46	78%	32.37	75%
Lighting power density	42.17	74%	42.77	70%	39.19	69%	35.46	77%	33.15	75%	31.12	73%
Zero energy building	**34.33**	60%	**35.32**	58%	**33.31**	59%	**29.40**	64%	**28.86**	65%	**27.52**	64%

Table 14. Annual electricity consumption in medium offices when energy efficiency design strategies were applied in six cities.



Strategies	Miami		Phoenix		Las Vegas		Baltimore		Chicago		Duluth	
	kWh	%	kWh	%	kWh	%	kWh	%	kWh	%	kWh	%
Existing	979.46	100%	962.66	100%	928.93	100%	861.89	100%	841.71	100%	815.63	100%
ASHRAE	837.35	85%	813.57	85%	779.96	84%	743.59	86%	710.34	84%	679.60	83%
Wall insulation	837.06	85%	812.18	84%	779.42	84%	743.99	86%	710.88	84%	680.03	83%
Roof insulation	835.26	85%	811.38	84%	778.28	84%	743.50	86%	710.16	84%	679.63	83%
Glazing	833.97	85%	812.47	84%	778.60	84%	736.80	85%	705.66	84%	675.90	83%
Wall, roof, glazing	831.07	85%	807.87	84%	775.53	83%	735.91	85%	702.90	84%	674.95	83%
Daylighting	808.16	83%	785.17	82%	752.04	81%	693.49	80%	662.71	79%	634.97	78%
Thermal mass	834.11	85%	810.71	84%	778.03	84%	740.01	86%	709.01	84%	678.39	83%
Cooling	789.21	81%	771.65	80%	745.94	80%	717.36	83%	692.23	82%	668.98	82%
Heating	837.35	85%	813.57	85%	779.96	84%	743.59	86%	710.34	84%	679.60	83%
Desk temp. reset	837.63	86%	813.25	84%	775.49	83%	735.29	85%	706.24	84%	673.30	83%
Thermostat setting	823.94	84%	803.47	83%	771.95	83%	736.40	85%	705.85	84%	677.04	83%
High efficiency appliance	**776.61**	79%	**753.51**	78%	**721.60**	78%	**686.90**	80%	**656.17**	78%	**627.70**	77%
Lighting power density	785.87	80%	762.47	79%	730.28	79%	695.29	81%	664.25	79%	635.39	78%
Zero energy building	**687.91**	70%	**671.86**	70%	**647.85**	70%	**615.19**	71%	**600.01**	71%	**580.36**	71%

Table 15. Annual electricity consumption in big offices when energy efficiency design strategies were applied in six cities.



Strategies	Miami		Phoenix		Las Vegas		Baltimore		Chicago		Duluth	
	kWh	%	kWh	%	kWh	%	kWh	%	kWh	%	kWh	%
Existing	8,434.45	100%	7,908.14	100%	7,628.74	100%	7,362.81	100%	7,208.44	100%	7,008.15	100%
ASHRAE	7,024.81	83%	6,504.25	82%	6,295.59	83%	6,230.11	85%	6,030.58	84%	5,840.00	83%
Wall insulation	7,018.63	83%	6,480.47	82%	6,286.61	82%	6,233.16	85%	6,032.37	84%	5,839.71	83%
Roof insulation	7,018.72	83%	6,492.37	82%	6,287.57	82%	6,231.17	85%	6,030.87	84%	5,840.43	83%
Glazing	6,990.91	83%	6,496.19	82%	6,282.87	82%	6,188.93	84%	6,001.42	83%	5,811.51	83%
Wall, roof, glazing	6,971.71	83%	6,454.23	82%	6,259.16	82%	6,167.17	84%	5,986.83	83%	5,810.50	83%
Daylighting	6,860.35	81%	6,354.17	80%	6,146.41	81%	5,948.58	81%	5,761.85	80%	5,591.17	80%
Thermal mass	7,015.76	83%	6,497.87	82%	6,303.30	83%	6,220.51	84%	6,019.85	84%	5,824.80	83%
Cooling	6,991.25	83%	6,482.99	82%	6,278.56	82%	6,213.37	84%	6,018.73	83%	5,832.62	83%
Heating	7,024.81	83%	6,504.25	82%	6,295.59	83%	6,230.11	85%	6,030.58	84%	5,840.00	83%
Desk temp. reset	7,027.99	83%	6,509.57	82%	6,301.91	83%	6,240.84	85%	6,037.40	84%	5,847.92	83%
Thermostat setting	6,892.82	82%	6,413.51	81%	6,217.27	81%	6,177.69	84%	5,988.71	83%	5,816.28	83%
High efficiency appliance	**6,483.88**	77%	**6,001.38**	76%	**5,800.62**	76%	**5,739.39**	78%	**5,560.10**	77%	**5,390.60**	77%
Lighting power density	6,625.46	79%	6,131.56	78%	5,929.05	78%	5,866.01	80%	5,681.53	79%	5,506.98	79%
Zero energy building	**6,002.71**	71%	**5,615.34**	71%	**5,449.33**	71%	**5,353.90**	73%	**5,224.29**	72%	**5,087.03**	73%

Medium and big office buildings have a roof-to-building area ratio less than one. Therefore, electricity output from PV systems was found unable to meet building electricity demand even though a combination of energy efficiency design strategies had been implemented. A typical PV system size at 30 kW DC can produce annual electricity equal to 4% to 5% electricity consumption in existing buildings. If all roof areas are covered with a PV system, the electricity proportion will increase to approximately 29% to 36% of electricity consumption in existing building. Data of annual electricity consumption when each energy efficiency design strategy was applied to small, medium, and big office buildings, including the percentage of consumption compared with existing buildings in six cities, can be found in Table 13 - Table 15. In a small office building, the best single strategy is daylighting followed by reduced lighting power density. In a big office building, the results follow the same trend as medium office buildings: using high efficiency appliances is the best single strategy, followed by reducing lighting power density.

Industrial buildings: Results from factory buildings show that reducing lighting power density was the most effective single strategy in reducing annual electricity consumption, followed by increasing cooling system efficiency in hot climates and using high efficiency appliances in mild and cold climates. For a combination of strategies, ZEB – which included almost all single strategies – can reduce annual electricity at around 30% to 35% from existing buildings (Figure 79). Factory buildings normally have large roof areas. A typical PV system size at 500 kW DC can produce annual electricity equal to 53% to 65% of electricity consumption in an existing building. If all roof areas facing southern orientation are covered with a PV system, the annual electricity output will be more than the existing building annual electricity consumption. Data of annual electricity consumption when each energy efficiency design strategy was applied to factory buildings compared with existing buildings in six cities can be found in Table 16.

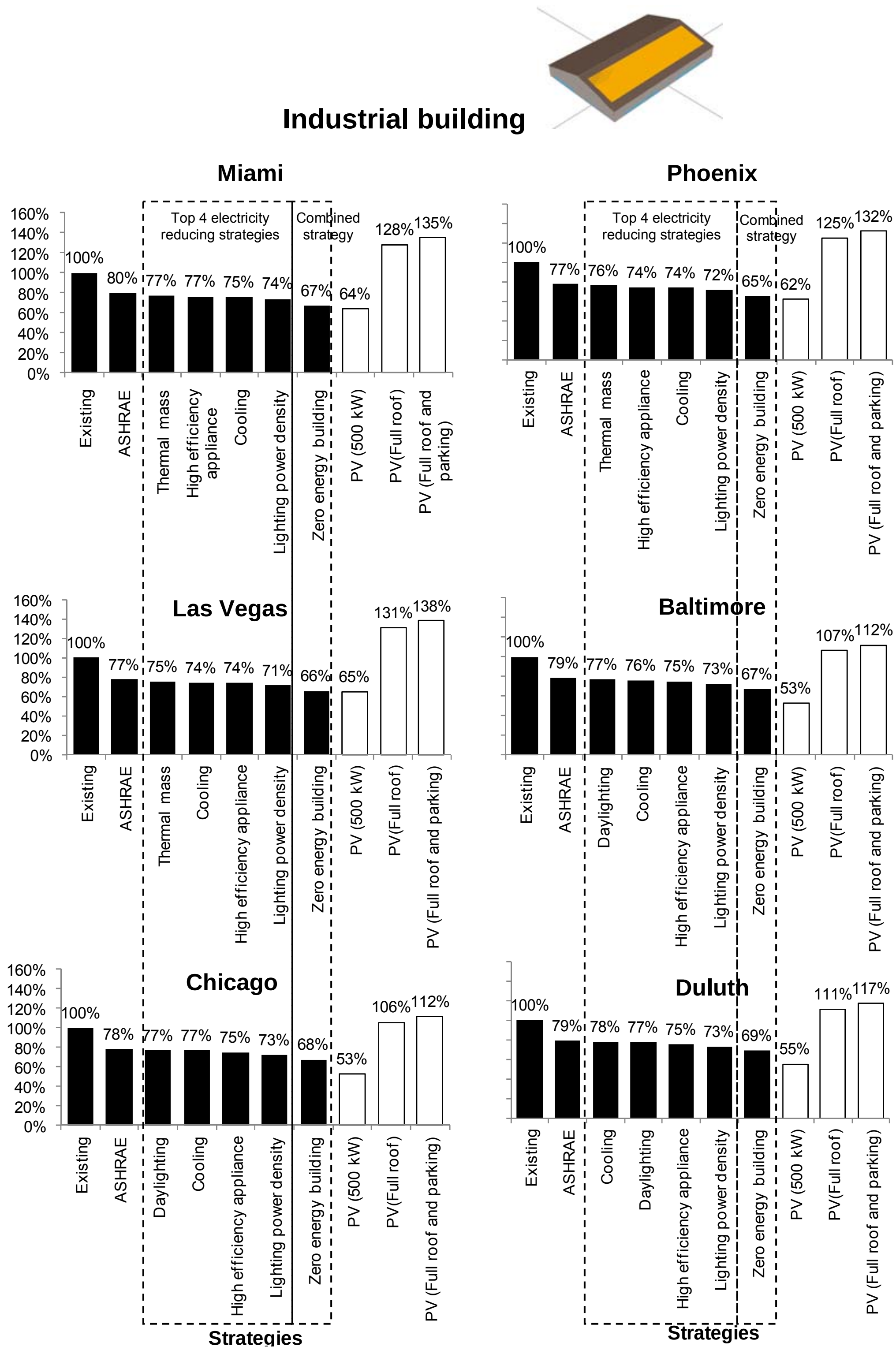
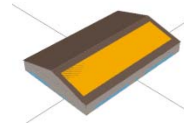


Figure 79. Top five annual electricity consumption reducing strategies compared with electricity consumption in existing and ASHRAE compliant buildings and electricity output from PV systems in factory buildings located in six cities.

Table 16. Annual electricity consumption in factory buildings when energy efficiency design strategies were applied in six cities.



Strategies	Miami		Phoenix		Las Vegas		Baltimore		Chicago		Duluth	
	kWh	%	kWh	%	kWh	%	kWh	%	kWh	%	kWh	%
Existing	1342.34	100%	1360.71	100%	1314.56	100%	1199.48	100%	1165.20	100%	1106.31	100%
ASHRAE	1069.75	80%	1052.09	77%	1015.18	77%	942.75	79%	914.36	78%	869.07	79%
Wall insulation	1068.72	80%	1052.17	77%	1015.04	77%	942.97	79%	914.55	78%	869.28	79%
Roof insulation	1069.42	80%	1051.59	77%	1014.88	77%	942.63	79%	914.30	78%	869.02	79%
Glazing	1069.77	80%	1051.90	77%	1014.86	77%	940.75	78%	912.49	78%	867.93	78%
Wall, roof, glazing	1070.44	80%	1053.07	77%	1014.36	77%	940.74	78%	912.45	78%	868.13	78%
Daylighting	1062.03	79%	1043.93	77%	1007.39	77%	924.81	77%	897.52	77%	853.89	77%
Thermal mass	1031.71	77%	1036.13	76%	991.60	75%	931.55	78%	905.73	78%	864.95	78%
Cooling	1013.11	75%	1001.90	74%	973.38	74%	915.93	76%	894.34	77%	859.46	78%
Heating	1069.75	80%	1052.09	77%	1015.18	77%	942.75	79%	914.36	78%	869.07	79%
Desk temp. reset	1064.50	79%	1048.47	77%	1008.65	77%	934.97	78%	909.39	78%	860.89	78%
Thermostat setting	1049.36	78%	1039.81	76%	1004.70	76%	931.74	78%	905.56	78%	865.06	78%
High efficiency appliance	1027.46	77%	1008.16	74%	972.78	74%	902.20	75%	875.42	75%	832.27	75%
Lighting power density	**994.78**	74%	**974.01**	72%	**939.74**	71%	**871.20**	73%	**845.26**	73%	**803.60**	73%
Zero energy building	**894.32**	67%	**887.82**	65%	**861.65**	66%	**806.46**	67%	**790.23**	68%	**762.22**	69%

Impact of building use schedule on annual electricity consumption: Electricity consumption in buildings with typical schedules compared with buildings with high use or 24-hour use schedules in Chicago are shown in Figure 80 - Figure 82. Detail data for all six types of buildings are shown in Table 17 - Table 19.

In residential buildings, 24-hour use buildings can benefit more from applying energy efficiency design strategies because buildings are used more during the day. However, electricity outputs from PV systems are the same while the overall electricity consumption increases. Therefore, electricity output from a typical 4 kW DC PV system cannot satisfy annual electricity consumption and accounts for 42% of the electricity load in existing small houses and 20% in existing medium houses.

In commercial buildings, the effect of the building use schedule to electricity saving proportions is less than in residential buildings. The proportions remain almost the same. However, the proportion of electricity produced from a PV system decreases because of the increased electricity consumption, while the PV electricity output is constant.

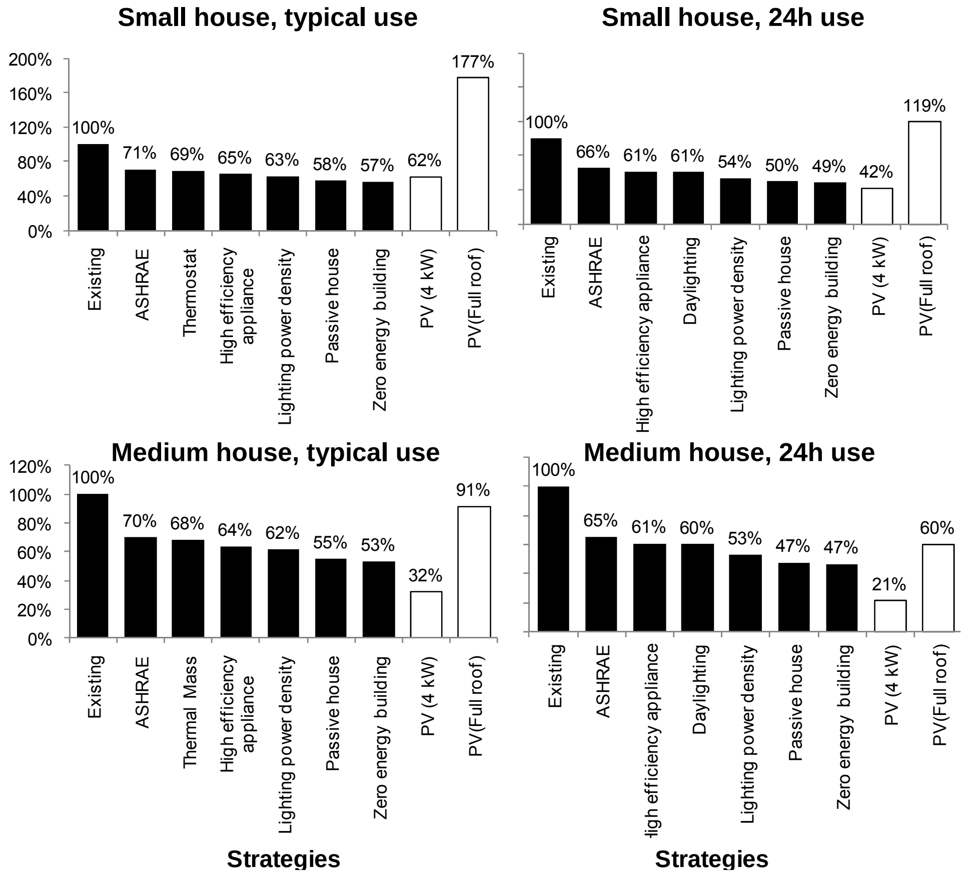


Figure 80. Comparison of annual electricity consumption between typical use schedule and 24-hour use schedule in residential buildings in Chicago.

Table 17. Comparison of annual electricity consumption between typical use schedule and 24-hour use schedule in residential buildings in Chicago.

Strategies	Small house				Medium house			
	Typical use		24h use		Typical use		24h use	
	kWh	%	kWh	%	kWh	%	kWh	%
Existing	6.94	100%	10.33	100%	13.46	100%	20.49	100%
ASHRAE	4.92	71%	6.78	66%	9.38	70%	13.33	65%
Wall insulation	4.88	70%	6.73	65%	9.34	69%	13.27	65%
Roof insulation	4.92	71%	6.79	66%	9.39	70%	13.33	65%
Glazing	4.88	70%	6.68	65%	9.25	69%	13.01	63%
Wall, roof, glazing	4.84	70%	6.63	64%	9.19	68%	12.94	63%
Daylighting	4.86	70%	6.25	61%	9.25	69%	12.29	60%
Thermal Mass	4.90	71%	6.70	65%	9.16	68%	12.82	63%
Cooling	4.90	71%	6.77	66%	9.31	69%	13.19	64%
Heating	4.92	71%	6.78	66%	9.38	70%	13.33	65%
Lighting power density	4.39	63%	5.53	54%	8.28	62%	10.78	53%
High efficiency appliance	4.52	65%	6.34	61%	8.55	64%	12.43	61%
Thermostat	4.81	69%	6.61	64%	9.18	68%	13.05	64%
Passive house	4.01	58%	5.13	50%	7.42	55%	9.72	47%
Zero energy building	3.92	57%	5.02	49%	7.17	53%	9.55	47%

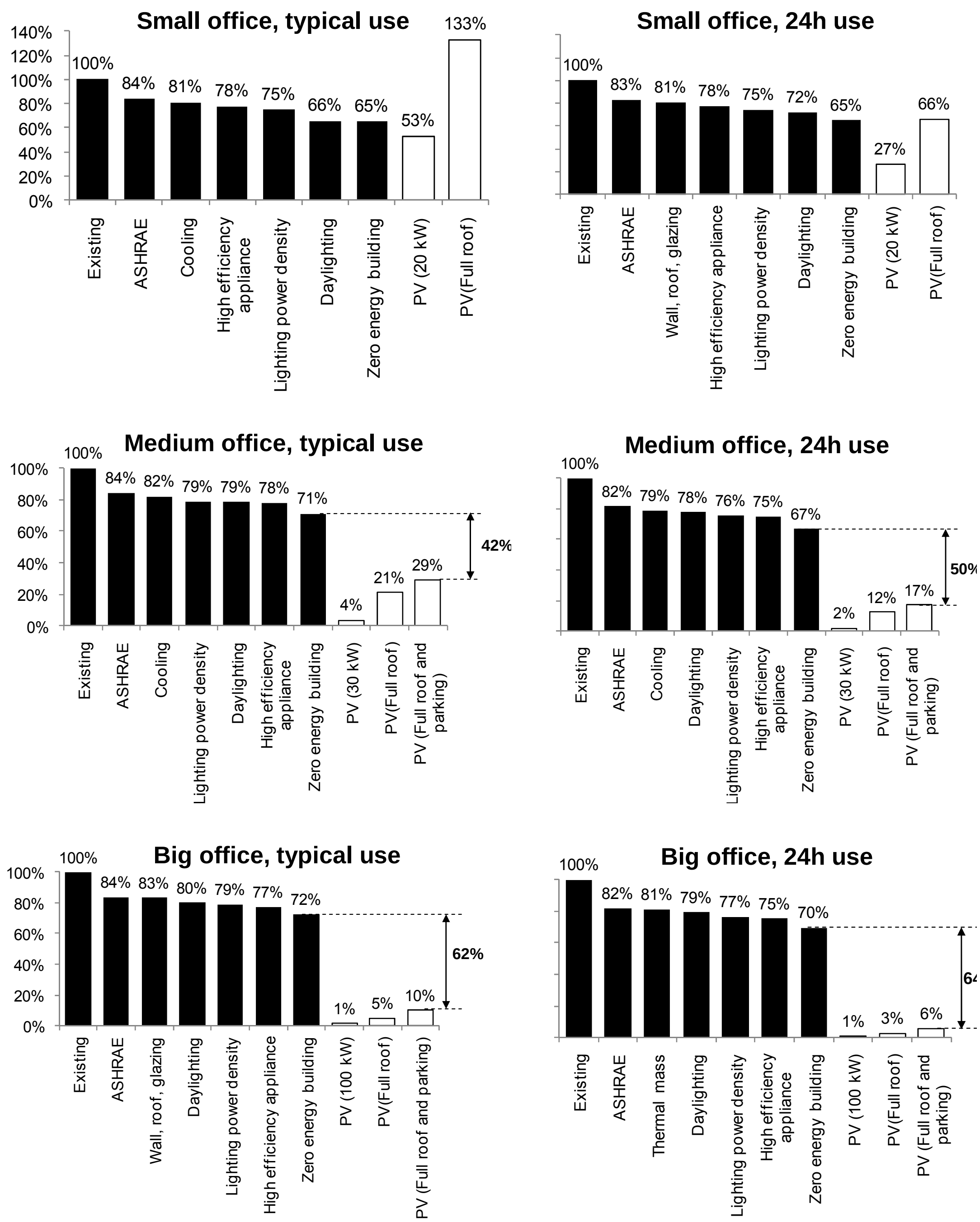


Figure 81. Comparison of annual electricity consumption between typical use schedule and 24-hour use schedule in commercial buildings in Chicago.

Table 18. Comparison of annual electricity consumption between typical use schedule and 24-hour use schedule in commercial buildings in Chicago.

Strategies	Small office				Medium office				Big office			
	Typical use		24h use		Typical use		24h use		Typical use		24h use	
	kWh	%	kWh	%	kWh	%	kWh	%	kWh	%	kWh	%
Existing	44.35	100%	88.84	100%	841.71	100%	1,425.73	100%	7,208.44	100%	12,383.29	100%
ASHRAE	37.12	84%	73.76	83%	710.34	84%	1,164.82	82%	6,030.58	84%	10,128.94	82%
Wall insulation	37.05	84%	73.61	83%	710.88	84%	1,163.90	82%	6,032.37	84%	10,117.99	82%
Roof insulation	37.11	84%	73.75	83%	710.16	84%	1,164.30	82%	6,030.87	84%	10,127.84	82%
Glazing	36.39	82%	71.95	81%	705.66	84%	1,159.89	81%	6,001.42	83%	10,104.28	82%
Wall, roof, glazing	36.30	82%	71.65	81%	702.90	84%	1,155.12	81%	5,986.83	83%	10,099.23	82%
Daylighting	29.08	66%	64.12	72%	662.71	79%	1,109.75	78%	5,761.85	80%	9,815.21	79%
Thermal mass	36.48	82%	72.03	81%	709.01	84%	1,158.87	81%	6,019.85	84%	10,039.09	81%
Cooling	35.98	81%	71.83	81%	692.23	82%	1,126.09	79%	6,018.73	83%	10,102.37	82%
Heating	37.12	84%	73.76	83%	710.34	84%	1,164.82	82%	6,030.58	84%	10,128.94	82%
Desk temp. reset	-	-	-	-	706.24	84%	1,142.87	80%	6,037.40	84%	10,058.31	81%
Thermostat setting	36.62	83%	72.99	82%	705.85	84%	1,158.10	81%	5,988.71	83%	10,093.40	82%
High efficiency appliance	34.46	78%	69.12	78%	656.17	78%	1,071.68	75%	5,560.10	77%	9,318.81	75%
Lighting power density	33.15	75%	66.28	75%	664.25	79%	1,078.69	76%	5,681.53	79%	9,474.93	77%
Zero energy building	28.86	65%	57.77	65%	600.01	71%	952.95	67%	5,224.29	72%	8,627.17	70%

In industrial buildings, the effect of the building use schedule to electricity saving proportions is small and almost remains the same. The proportion of electricity produced from a PV system decreases because of the increased electricity consumption, while the PV electricity output is constant. In typical use, increasing the PV system size can eventually satisfy the annual electricity need, while in 24-hour use schedules annual electricity consumption increases and a PV system cannot meet the demand with all available roof areas.

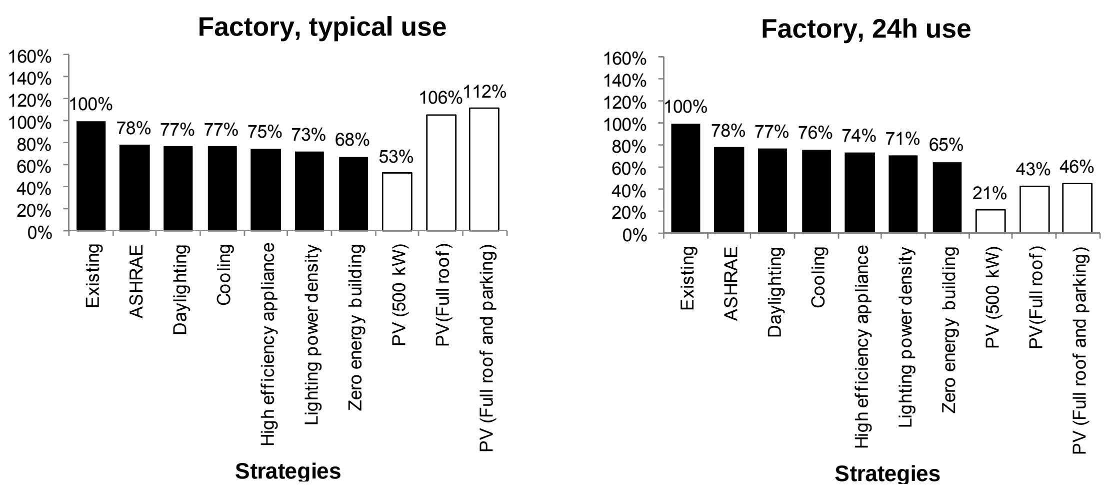


Figure 82. Comparison of annual electricity consumption between typical use schedule and 24-hour use schedule in industrial buildings in Chicago.

Table 19. Comparison of annual electricity consumption between typical use schedule and 24-hour use schedule industrial buildings in Chicago.

Strategies	Factory			
	Typical use		24h use	
	kWh	%	kWh	%
Existing	1165.20	100%	2,854.43	100%
ASHRAE	914.36	78%	2,230.36	78%
Wall insulation	914.55	78%	2,232.56	78%
Roof insulation	914.30	78%	2,230.27	78%
Glazing	912.49	78%	2,226.05	78%
Wall, roof, glazing	912.45	78%	2,227.98	78%
Daylighting	897.52	77%	2,204.24	77%
Thermal mass	905.73	78%	2,218.48	78%
Cooling	894.34	77%	2,174.32	76%
Heating	914.36	78%	2,230.36	78%
Desk temp. reset	909.39	78%	2,230.36	78%
Thermostat setting	905.56	78%	2,207.66	77%
High efficiency appliance	875.42	75%	2,103.66	74%
Lighting power density	845.26	73%	2,024.59	71%
Zero energy building	790.23	68%	1,861.98	65%

3.2.2 Peak electricity reduction.

Residential buildings: Results from small houses show that increasing building envelope insulations and glazing performance was the most effective single strategy in reducing peak electricity consumption in hot climates. In mild and cold climates, the best strategies are increasing cooling system efficiency and reducing lighting power density. For a combination of strategies, ZEB – which included almost all single strategies – can reduce peak electricity use approximately 8% to 16% further from ASHRAE-compliant buildings (Figure 83). Table 20 shows data of peak electricity demand when each energy efficiency design strategy was applied to small houses and the percentage of consumption compared with existing buildings in six cities. Table 21 shows results of medium houses, where increasing building envelope insulation was the best strategy in hot climates. In mild climates, reducing lighting power density was the best single strategy and in very cold climates, thermal mass was the best strategy.

PV electricity output is available during day time when people are not at home; therefore, it has little ability to reduce peak power demand, which usually occurs during late afternoon for residential buildings with typical use. Peak electricity outputs from a typical size at 4 kW DC PV were approximately 4% to 7% compared with peak electricity demand in small residential buildings. With all southern roof areas covered with PV systems size at 10 kW DC, the peak electricity outputs were increased to approximately 6% to 11%.

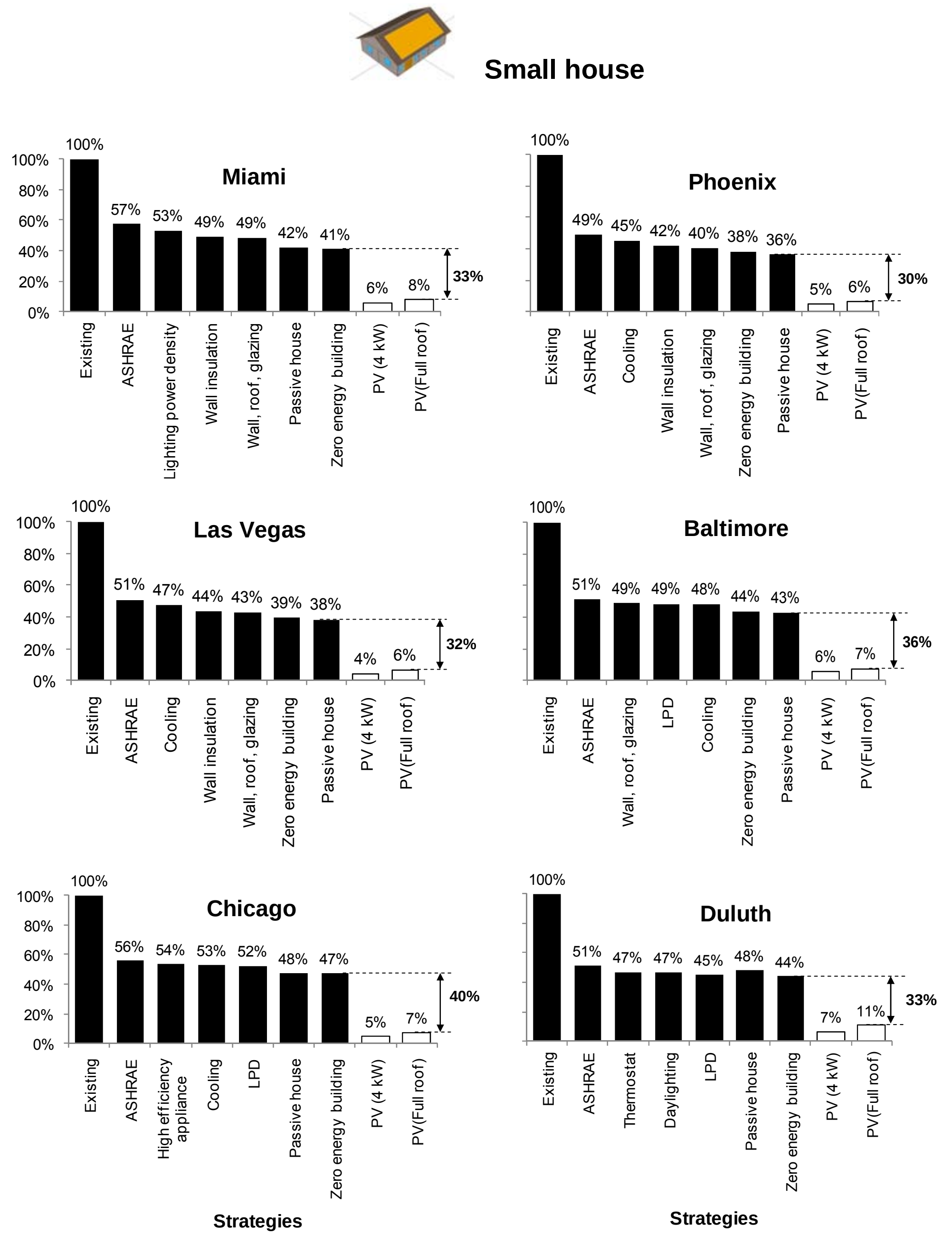
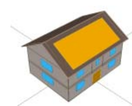


Figure 83. Top five peak electricity reducing strategies compared with peak electricity demand in existing and ASHRAE compliant buildings and peak electricity output from PV systems in small houses located in six cities.

Table 20. Peak electricity demand in small houses in six cities when energy efficiency design strategies were applied.

Strategies	Miami		Phoenix		Las Vegas		Baltimore		Chicago		Duluth	
	kW	%	kW	%	kW	%	kW	%	kW	%	kW	%
Existing	5.39	100%	8.12	100%	7.10	100%	5.22	100%	4.48	100%	4.25	100%
ASHRAE	3.09	57%	3.98	49%	3.62	51%	2.68	51%	2.51	56%	2.18	51%
Wall insulation	2.66	49%	3.42	42%	3.10	44%	2.63	50%	2.47	55%	2.17	51%
Roof insulation	3.09	57%	3.98	49%	3.62	51%	2.68	51%	2.51	56%	2.18	51%
Glazing	3.05	57%	3.85	47%	3.53	50%	2.58	49%	2.45	55%	2.05	48%
Wall, roof, glazing	**2.62**	49%	**3.28**	40%	**3.04**	43%	2.54	49%	2.43	54%	2.04	48%
Daylighting	3.04	56%	3.92	48%	3.50	49%	2.57	49%	2.41	54%	1.99	47%
Thermal Mass	3.02	56%	3.88	48%	3.56	50%	2.61	50%	2.48	55%	2.07	49%
Cooling	2.90	54%	3.69	45%	3.37	47%	**2.53**	48%	2.37	53%	2.08	49%
Heating	3.09	57%	3.98	49%	3.62	51%	2.68	51%	2.51	56%	2.18	51%
LPD	2.87	53%	3.74	46%	3.45	49%	2.54	49%	**2.35**	52%	**1.93**	45%
High efficiency appliance	2.98	55%	3.87	48%	3.47	49%	2.58	49%	2.41	54%	2.06	48%
Thermostat	3.03	56%	3.98	49%	3.62	51%	2.62	50%	2.50	56%	2.00	47%
Passive house	**2.27**	42%	**2.95**	36%	**2.73**	38%	**2.25**	43%	**2.13**	48%	**2.05**	48%
Zero energy building	**2.21**	41%	**3.11**	38%	**2.80**	39%	**2.28**	44%	**2.13**	47%	**1.88**	44%

Table 21. Peak electricity demand in medium houses in six cities when energy efficiency design strategies were applied.



Strategies	Miami		Phoenix		Las Vegas		Baltimore		Chicago		Duluth	
	kW	%	kW	%	kW	%	kW	%	kW	%	kW	%
Existing	9.07	100%	13.77	100%	12.46	100%	8.82	100%	8.25	100%	7.81	100%
ASHRAE	5.13	57%	6.72	49%	6.32	51%	4.62	52%	4.54	55%	4.20	54%
Wall insulation	4.40	48%	5.78	42%	5.51	44%	4.49	51%	4.42	54%	4.19	54%
Roof insulation	5.13	57%	6.73	49%	6.32	51%	4.62	52%	4.54	55%	4.20	54%
Glazing	5.03	56%	6.45	47%	6.06	49%	4.43	50%	4.31	52%	3.94	50%
Wall, roof, glazing	**4.29**	47%	**5.55**	40%	**5.24**	42%	4.31	49%	4.22	51%	3.93	50%
Daylighting	4.94	54%	6.45	47%	6.04	48%	4.31	49%	4.23	51%	3.83	49%
Thermal Mass	4.93	54%	6.49	47%	5.95	48%	4.30	49%	4.15	50%	**3.37**	43%
Cooling	4.85	54%	6.27	46%	5.92	47%	4.39	50%	4.32	52%	4.01	51%
Heating	5.13	57%	6.72	49%	6.32	51%	4.62	52%	4.54	55%	4.20	54%
LPD	4.65	51%	6.21	45%	5.94	48%	**4.19**	47%	**4.13**	50%	3.71	47%
High efficiency appliance	4.90	54%	6.47	47%	6.04	48%	4.39	50%	4.28	52%	3.97	51%
Thermostat	5.02	55%	6.72	49%	6.32	51%	4.59	52%	4.48	54%	4.08	52%
Passive house	**3.73**	41%	**4.69**	34%	**4.66**	37%	**3.76**	43%	**3.74**	45%	**3.48**	44%
Zero energy building	**3.57**	39%	**4.50**	33%	**4.44**	36%	**3.42**	39%	**3.40**	41%	**3.07**	39%

Commercial buildings: Results from medium office buildings show that increasing cooling system efficiency was the best single strategy in reducing peak electricity demand in hot and mild climates. In cold climates, daylighting was also the best strategy. They resulted in reducing peak electricity demand at almost the same level. ZEB can reduce peak electricity demand at around 20% from ASHRAE-compliant buildings (Figure 84).

Data of peak electricity demand in small, medium, and big office buildings and their percentage of demand compared with existing buildings in six cities can be found in Table 22 - Table 24.

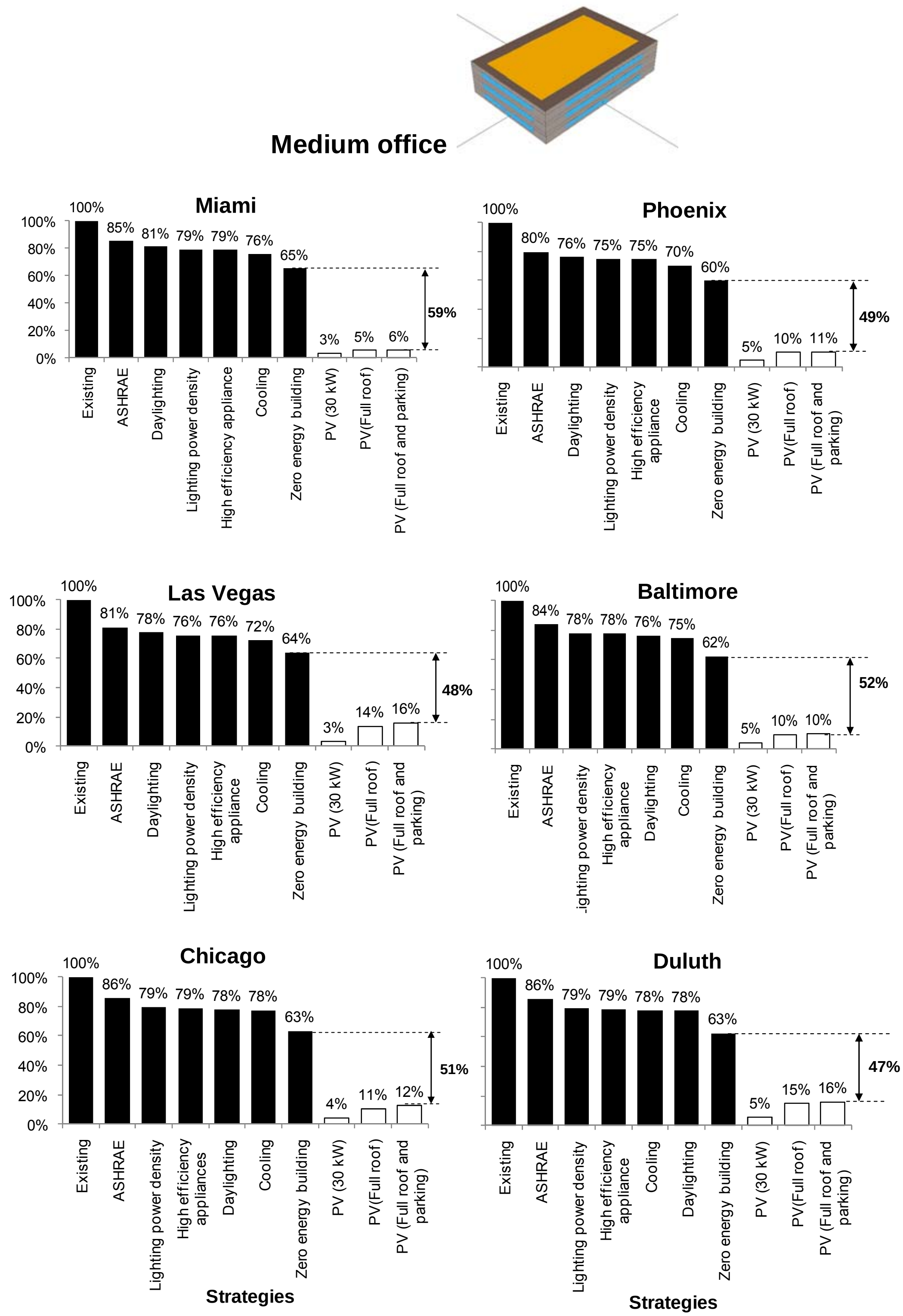
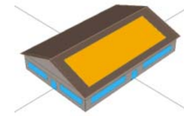


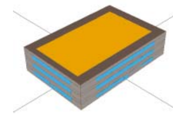
Figure 84. Top five peak electricity reducing strategies compared with peak electricity demand in existing and ASHRAE compliant buildings and peak electricity output from PV systems in medium office buildings located in six cities.

Table 22. Peak electricity demand in small offices in six cities when energy efficiency design strategies were applied.



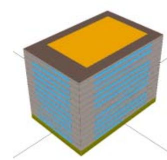
Strategies	Miami		Phoenix		Las Vegas		Baltimore		Chicago		Duluth	
	kW	%	kW	%	kW	%	kW	%	kW	%	kW	%
Existing	25.58	100%	35.01	100%	33.98	100%	25.02	100%	23.89	100%	23.39	100%
ASHRAE	20.63	81%	25.10	72%	25.77	76%	20.72	83%	19.59	82%	19.12	82%
Wall insulation	20.39	80%	24.75	71%	24.85	73%	20.59	82%	19.45	81%	19.01	81%
Roof insulation	20.56	80%	25.10	72%	25.76	76%	20.70	83%	19.56	82%	19.09	82%
Glazing	20.86	82%	25.63	73%	26.35	78%	19.86	79%	19.00	80%	17.88	76%
Wall, roof, glazing	20.45	80%	24.98	71%	25.95	76%	19.48	78%	18.82	79%	17.74	76%
Daylighting	19.13	75%	22.67	65%	22.85	67%	**17.17**	69%	**15.96**	67%	**15.27**	65%
Thermal mass	19.81	77%	24.77	71%	23.95	70%	20.28	81%	19.33	81%	18.45	79%
Cooling	**17.97**	70%	**21.38**	61%	**21.89**	64%	18.09	72%	17.22	72%	16.90	72%
Heating	20.63	81%	25.10	72%	25.77	76%	20.72	83%	19.59	82%	19.12	82%
Thermostat setting	20.15	79%	25.04	72%	25.69	76%	20.31	81%	19.17	80%	18.74	80%
High efficiency appliance	19.73	77%	24.22	69%	24.86	73%	19.82	79%	18.70	78%	18.23	78%
Lighting power density	19.09	75%	23.53	67%	24.16	71%	19.15	77%	18.04	76%	17.59	75%
Zero energy building	**14.96**	58%	**18.58**	53%	**18.78**	55%	**14.27**	57%	**13.81**	58%	**13.08**	56%

Table 23. Peak electricity demand in medium offices in six cities when energy efficiency design strategies were applied.



Strategies	Miami		Phoenix		Las Vegas		Baltimore		Chicago		Duluth	
	kW	%	kW	%	kW	%	kW	%	kW	%	kW	%
Existing	314.42	100%	368.98	100%	352.13	100%	311.25	100%	291.92	100%	279.85	100%
ASHRAE	267.38	85%	294.70	80%	286.22	81%	261.13	84%	250.43	86%	239.55	86%
Wall insulation	265.24	84%	291.08	79%	284.11	81%	260.89	84%	251.12	86%	241.62	86%
Roof insulation	265.20	84%	294.23	80%	285.97	81%	259.56	83%	250.29	86%	239.67	86%
Glazing	267.87	85%	299.56	81%	291.65	83%	256.07	82%	244.35	84%	230.66	82%
Wall, roof, glazing	264.34	84%	293.44	80%	289.39	82%	253.69	82%	240.35	82%	225.23	80%
Daylighting	254.61	81%	281.21	76%	273.55	78%	237.99	76%	**227.22**	78%	**217.10**	78%
Thermal mass	259.91	83%	287.42	78%	275.87	78%	260.19	84%	248.90	85%	237.44	85%
Cooling	**237.93**	76%	**259.79**	70%	**254.74**	72%	**232.15**	75%	**226.40**	78%	**217.53**	78%
Heating	267.38	85%	294.70	80%	286.22	81%	261.13	84%	250.43	86%	239.55	86%
Desk temp. reset	267.42	85%	294.73	80%	286.22	81%	261.56	84%	250.60	86%	240.04	86%
Thermostat setting	260.74	83%	291.29	79%	285.51	81%	256.86	83%	243.89	84%	232.18	83%
High efficiency appliance	248.50	79%	275.19	75%	266.92	76%	242.21	78%	230.47	79%	220.24	79%
Lighting power density	**249.29**	79%	**275.74**	75%	**267.45**	76%	**242.93**	78%	**232.06**	79%	**221.83**	79%
Zero energy building	**204.25**	65%	**220.59**	60%	**225.11**	64%	**193.87**	62%	**185.04**	63%	**175.11**	63%

Table 24. Peak electricity demand in big offices in six cities when energy efficiency design strategies were applied.



Strategies	Miami		Phoenix		Las Vegas		Baltimore		Chicago		Duluth	
	kW	%	kW	%	kW	%	kW	%	kW	%	kW	%
Existing	2,833.52	100%	2,727.16	100%	2,834.53	100%	2,664.97	100%	2,489.78	100%	2,428.02	100%
ASHRAE	2,439.82	86%	2,238.37	82%	2,232.83	79%	2,142.05	80%	2,057.30	83%	2,142.57	88%
Wall insulation	2,431.41	86%	2,225.76	82%	2,212.64	78%	2,139.45	80%	2,061.96	83%	2,152.50	89%
Roof insulation	2,435.69	86%	2,230.08	82%	2,218.10	78%	2,130.26	80%	2,056.28	83%	2,139.43	88%
Glazing	2,432.78	86%	2,244.92	82%	2,241.80	79%	2,112.98	79%	2,007.87	81%	2,064.91	85%
Wall, roof, glazing	2,401.68	85%	2,199.85	81%	2,201.88	78%	2,075.91	78%	1,978.69	79%	2,061.90	85%
Daylighting	2,372.86	84%	2,196.51	81%	2,174.57	77%	2,040.08	77%	1,915.16	77%	2,003.36	83%
Thermal mass	2,275.28	80%	2,131.13	78%	2,104.52	74%	2,093.68	79%	2,014.19	81%	2,089.72	86%
Cooling	2,416.07	85%	2,216.49	81%	2,212.83	78%	2,124.28	80%	2,038.81	82%	2,122.72	87%
Heating	2,439.82	86%	2,238.37	82%	2,232.83	79%	2,142.05	80%	2,057.30	83%	2,142.57	88%
Desk temp. reset	2,440.04	86%	2,238.72	82%	2,232.96	79%	2,147.92	81%	2,054.58	83%	2,159.35	89%
Thermostat setting	2,366.13	84%	2,204.47	81%	2,209.35	78%	2,081.43	78%	1,983.70	80%	2,032.47	84%
High efficiency appliance	**2,246.08**	79%	**2,060.10**	76%	**2,068.31**	73%	**1,967.67**	74%	**1,865.34**	75%	**1,945.99**	80%
Lighting power density	2,282.94	81%	2,090.80	77%	2,100.86	74%	2,010.36	75%	1,901.10	76%	1,988.32	82%
Zero energy building	**1,908.90**	67%	**1,887.56**	69%	**1,876.24**	66%	**1,730.77**	65%	**1,701.27**	68%	**1,581.56**	65%

A typical PV system size at 30 kW DC in medium office buildings can produce peak electricity equal to approximately 3% to 5%. If all roof areas are covered with PV systems, the electricity output could increase to approximately 6% to 16% of peak electricity demand in existing buildings.

In small office buildings, increasing cooling system efficiency was the best single strategy in hot and mild climates. In mild and cold climates, daylighting was the best single strategy to reduce peak electricity demand. In big office buildings, using high efficiency appliances was the best single strategy, followed by reducing lighting power density in all kinds of climate.

Industrial buildings: Results from factory buildings show that increasing cooling system efficiency was the best strategy in reducing peak electricity demand followed by reducing lighting power density. Thermal mass and using high efficiency appliances ranked third. For combinations of strategies, ZEB – which included almost all single strategies – can reduce peak electricity demand at around 15% to 17% from existing buildings (Figure 85).

A typical PV system size at 500 kW DC can produce peak electricity equal to 15% to 23% of electricity peak demand in existing buildings. If all roof areas facing a southern orientation are covered with PV systems, the peak electricity output would equal up to 29%. Data of peak electricity demand when each energy efficiency design strategies was applied to factory buildings compared with existing buildings in six cities can be found in Figure 85 and Table 25.

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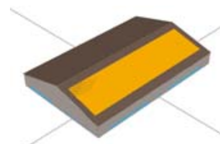


Industrial building

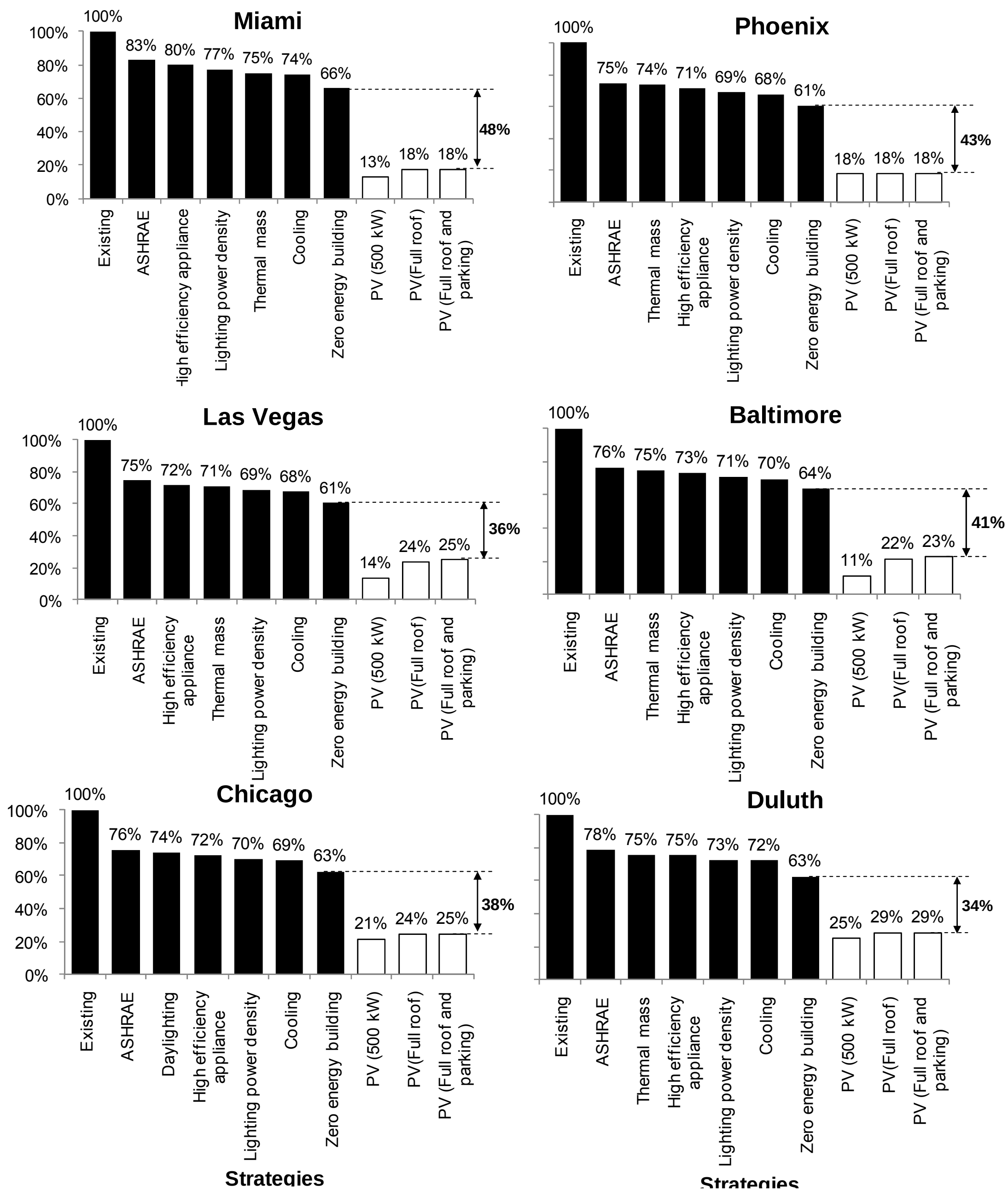
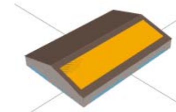


Figure 85. Top five peak electricity reducing strategies compared with peak electricity demand in existing and ASHRAE compliant buildings and peak electricity output from PV systems in factory buildings located in six cities.

Table 25. Peak electricity demand in factory buildings in six cities when energy efficiency design strategies were applied.



Strategies	Miami		Phoenix		Las Vegas		Baltimore		Chicago		Duluth	
	kW	%	kW	%	kW	%	kW	%	kW	%	kW	%
Existing	562.25	100%	568.56	100%	575.55	100%	544.13	100%	528.41	100%	493.91	100%
ASHRAE	465.96	83%	424.38	75%	429.24	75%	415.86	76%	398.99	76%	387.44	78%
Wall insulation	466.32	83%	423.93	75%	429.05	75%	415.77	76%	398.92	75%	386.60	78%
Roof insulation	465.53	83%	424.31	75%	429.15	75%	415.83	76%	398.98	76%	387.11	78%
Glazing	465.93	83%	424.48	75%	429.33	75%	415.73	76%	399.19	76%	383.94	78%
Wall, roof, glazing	465.52	83%	424.47	75%	429.05	75%	415.60	76%	399.23	76%	382.91	78%
Daylighting	463.05	82%	420.79	74%	426.63	74%	408.96	75%	390.96	74%	376.35	76%
Thermal mass	422.59	75%	420.12	74%	408.37	71%	407.47	75%	394.14	75%	372.68	75%
Cooling	**418.38**	74%	**385.93**	68%	**389.51**	68%	**379.06**	70%	**366.33**	69%	**356.57**	72%
Heating	465.96	83%	424.38	75%	429.24	75%	415.86	76%	398.99	76%	387.44	78%
Desk temp. reset	465.87	83%	424.38	75%	429.24	75%	415.86	76%	398.89	75%	385.11	78%
Thermostat setting	457.04	81%	424.38	75%	429.24	75%	416.55	77%	403.49	76%	379.16	77%
High efficiency appliance	448.90	80%	406.47	71%	411.52	72%	398.62	73%	381.99	72%	371.94	75%
Lighting power density	434.94	77%	391.60	69%	396.85	69%	386.08	71%	370.15	70%	358.59	73%
Zero energy building	**370.83**	66%	**344.33**	61%	**348.37**	61%	**345.59**	64%	**331.40**	63%	**309.02**	63%

Hourly electricity profiles in winter and summer: An hourly electricity demand graph is useful when examining details of how peak electricity is reduced by applying energy efficiency design strategies and installing PV systems (Figure 86).

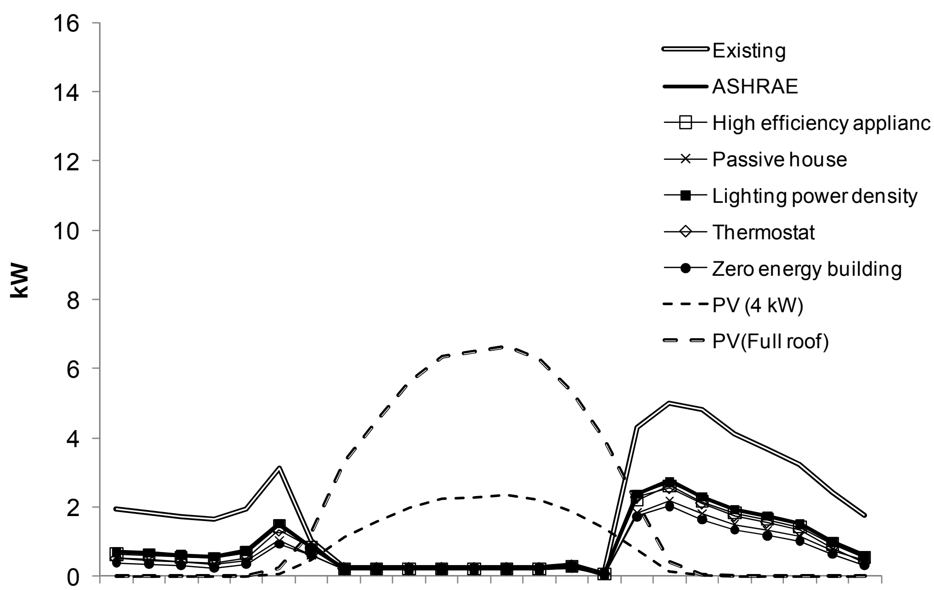


Figure 86. Example of residential hourly electricity demand profiles in summer compared with electricity output profile from PV systems.

Potential of energy efficiency design strategies and electricity output from PV systems in reducing peak electricity demand is shown in Figure 87. In this graph, the double line represents existing electricity demand. The line with bold circle symbols represents hourly electricity demand after ZEB was applied. The positive grayed area is electricity bought from electric utility companies after PV electricity output was used. The negative grayed area is excess electricity from PV systems sold back to the electric grid. The example in Figure 87 shows that peak demand in this particular day in summer can be reduced 68% with energy efficiency design strategies and electricity from PV systems.

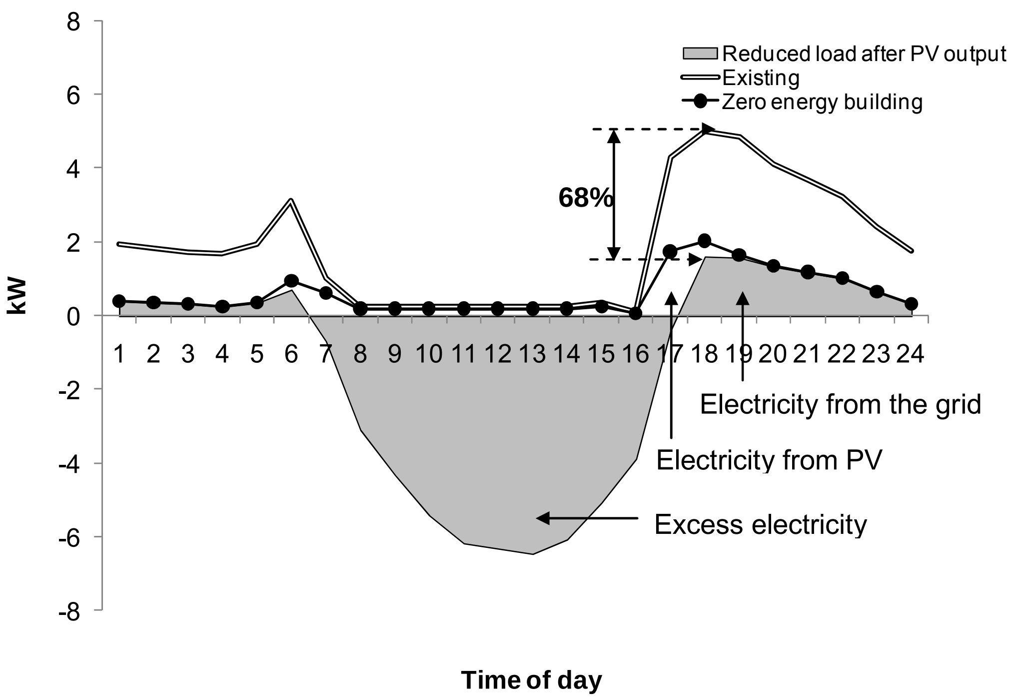


Figure 87. Hourly electricity profile after load reduction from energy efficiency design strategies and PV electricity output were applied.

Figure 88 - Figure 93 show hourly load profiles of residential, commercial, and industrial buildings when ZEB strategy and PV typical-size systems were applied, demonstrating the potential of peak electricity reduction in summer days and winter days in six cities.

In residential buildings, peak load demand occurs during 5 p.m. to 7 p.m. in summer and during 6 p.m. to 7 p.m. in winter. In summer, the days are longer than in winter, and electricity from PV systems can help in reducing peak demand in the afternoon period before the sun sets. On the selected summer day, peak electricity demand can be reduced approximately 63% to 77% with a combination of energy efficiency design and PV system output. In winter, these percentages in reduction were decreased to approximately 40% in mild and cold climates. However, electricity peak demand was also significantly less than the demand in summer (Figure 88 and Figure 89).

In commercial buildings with typical use, peak electricity demand occurs during the day. Energy efficiency design strategies can help bring overall electricity demand down. In summer, when the day is longer than typical office working hours, electricity from PV systems can help bringing peak electricity demand down further. In winter, with a shorter day length, PV electricity output can help reduce electricity consumption during the day but has almost no effect on peak electricity demand at the end or the beginning of the day. Peak electricity demand can be reduced approximately 41% to 55% in summer and 30% to 46% in winter. For medium and big office buildings with limited roof area, PV system size is also limited. There is almost no excess electricity sold back to the electric grids during daytime on business days.

In industrial buildings with typical use, peak electricity demand occurs during the day. With energy efficiency design strategies, peak electricity demand is reduced. In summer, this peak demand can be reduced further by using electricity output from PV systems installed on the rooftops of factory buildings. However, in winter when the duration of days are shorter, electricity output from PV systems can help bring electricity demand down during the day, but not peak electricity demand at the beginning or end of the day. With combinations of energy efficiency design strategies and electricity from PV systems, peak electricity demand can be reduced approximately 74% to 85% in summer and 29% to 46% in winter. Factory buildings have large roof areas and therefore can accommodate large size PV systems. Excess electricity from PV systems can be sold back to the electric grids during the daytime on business days.

Residential buildings

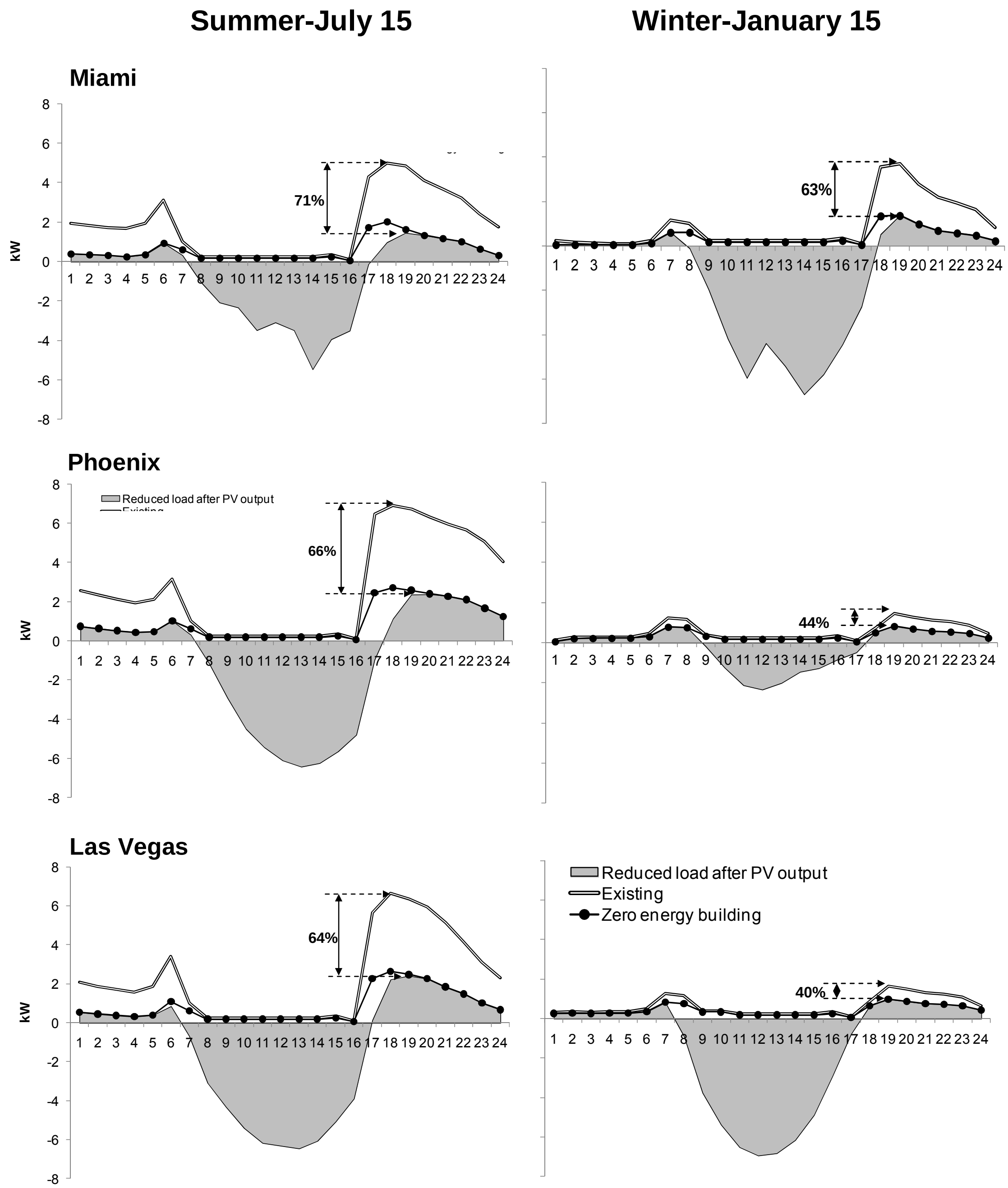


Figure 88. Examples of the potential that ZEB and PV systems have for reducing summer and winter peak electricity load demand in small houses located in Miami, Phoenix, and Las Vegas.

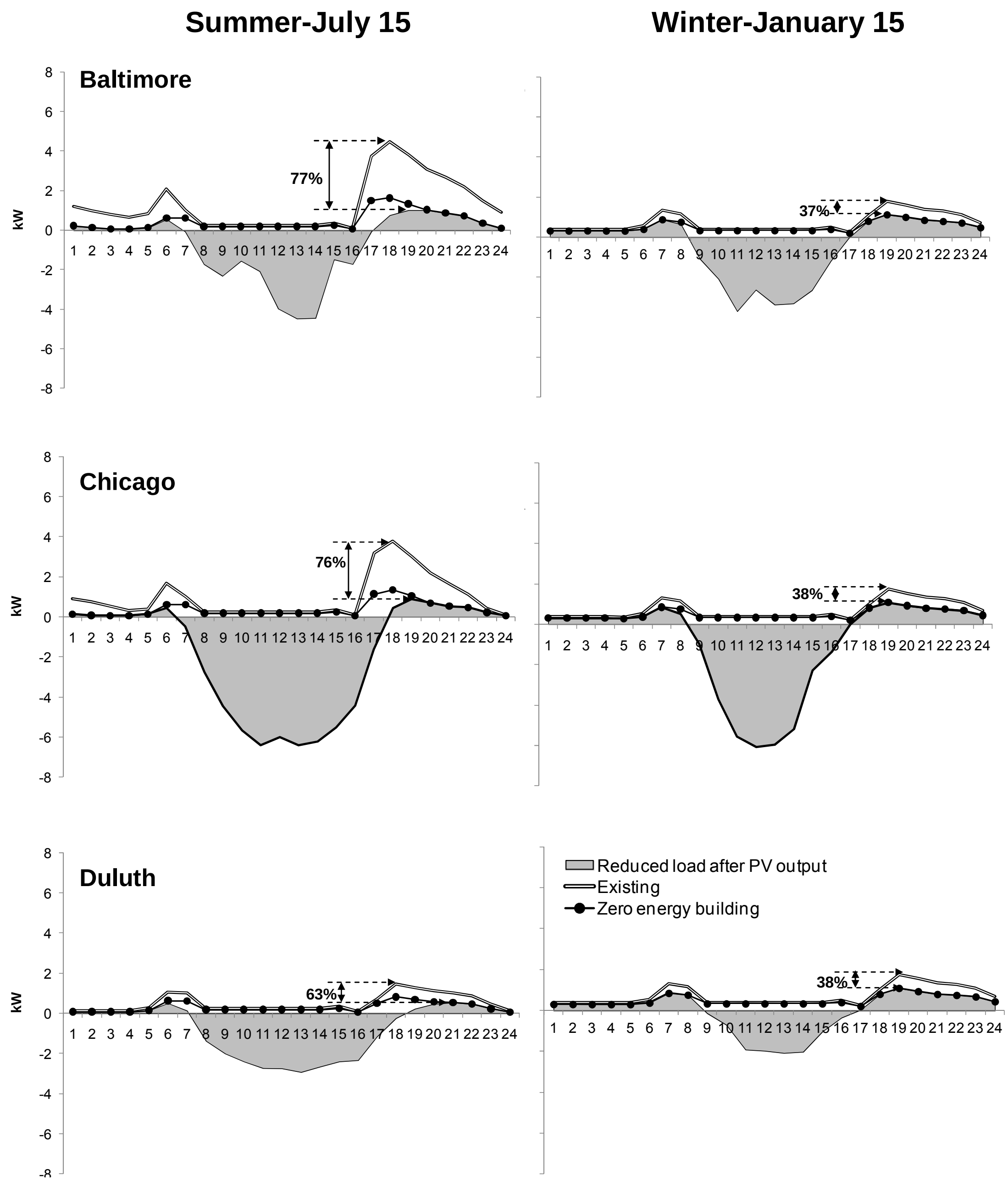


Figure 89. Examples of the potential that ZEB and PV systems have for reducing summer and winter peak electricity load demand in small houses located in Baltimore, Chicago, and Duluth.

Commercial buildings

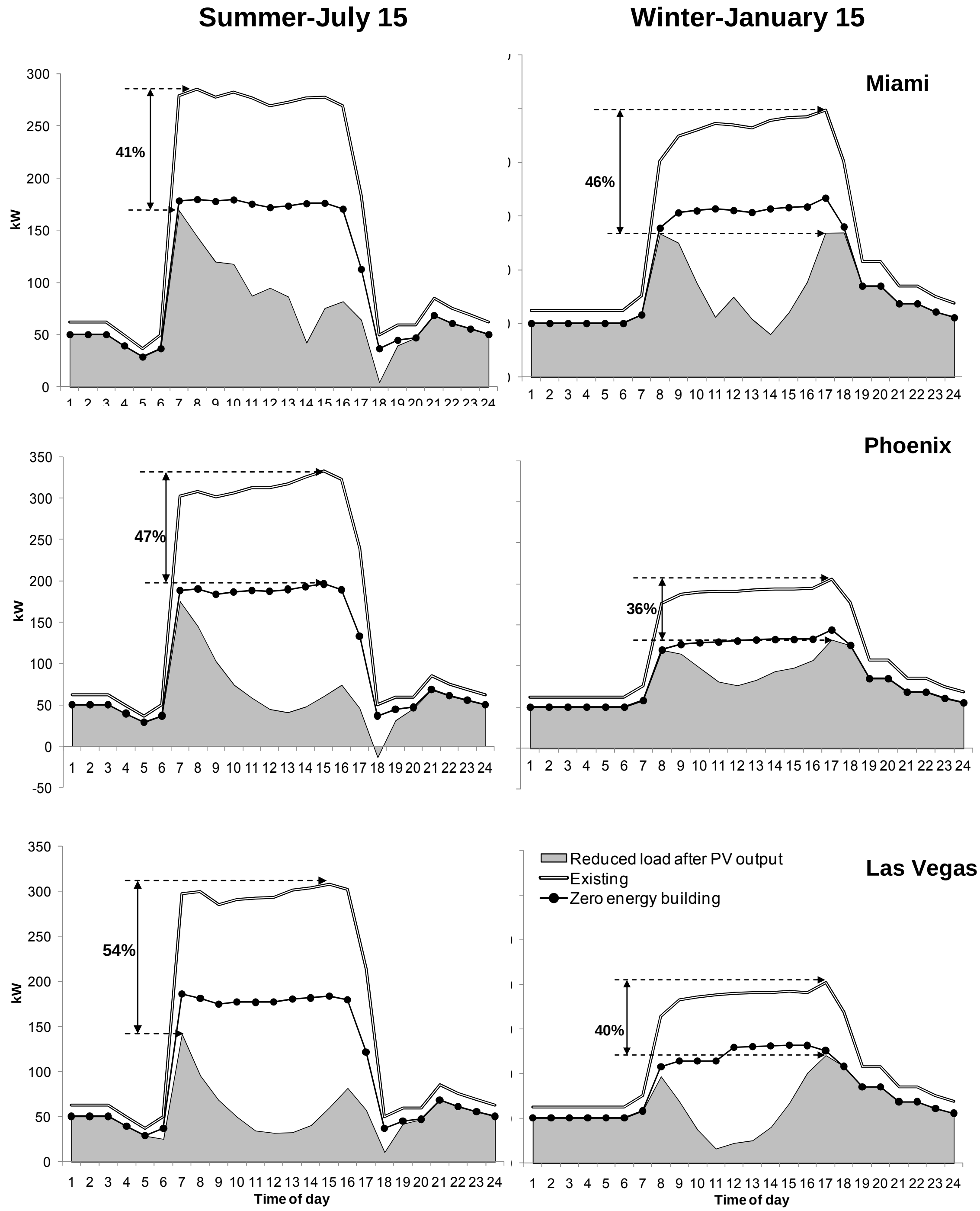


Figure 90. Examples of the potential that ZEB and PV systems have for reducing summer and winter peak electricity load demand in medium office buildings located in Miami, Phoenix, and Las Vegas.

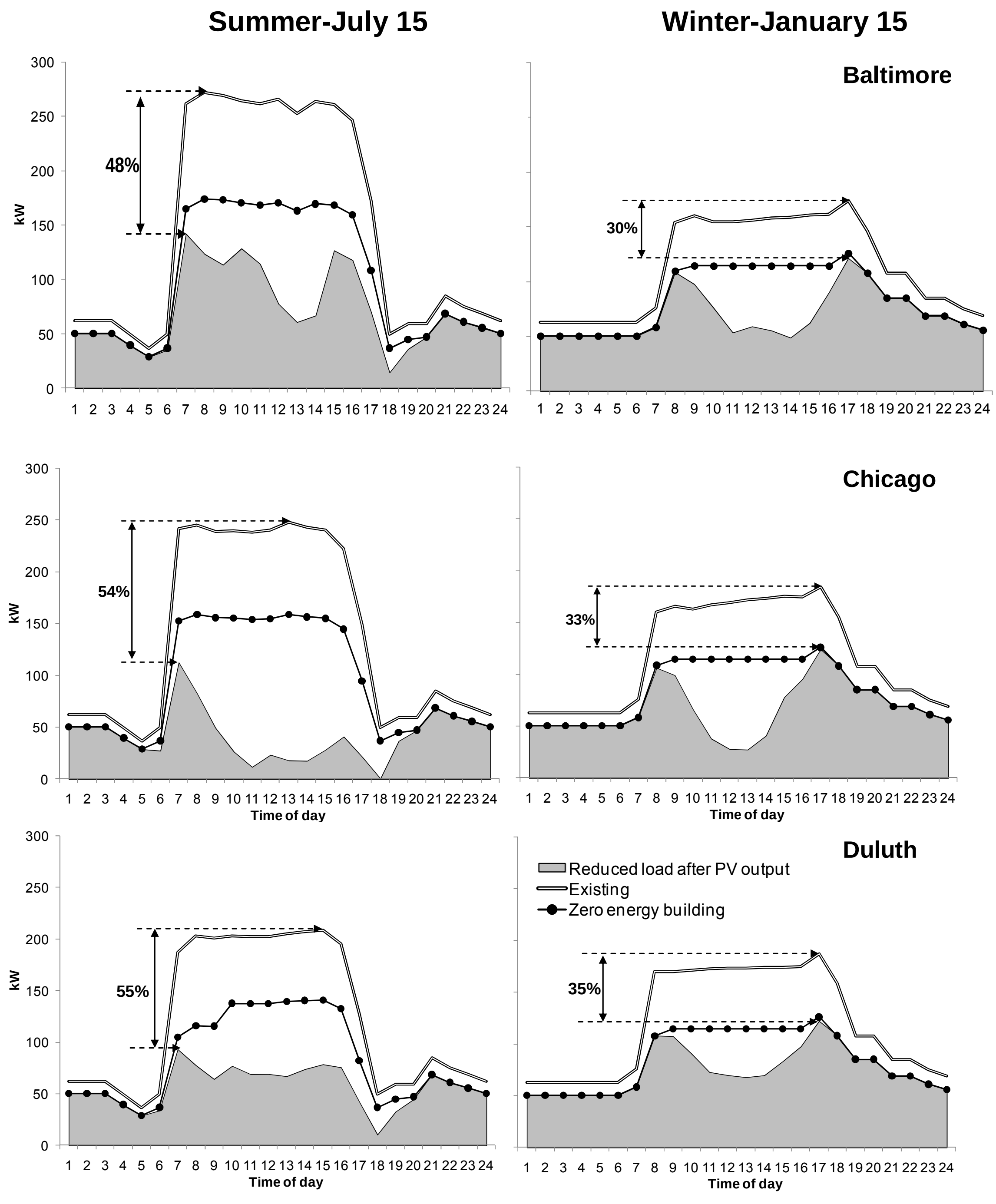


Figure 91. Examples of the potential that ZEB and PV systems have for reducing summer and winter peak electricity load demand in medium office buildings in Baltimore, Chicago, and Duluth.

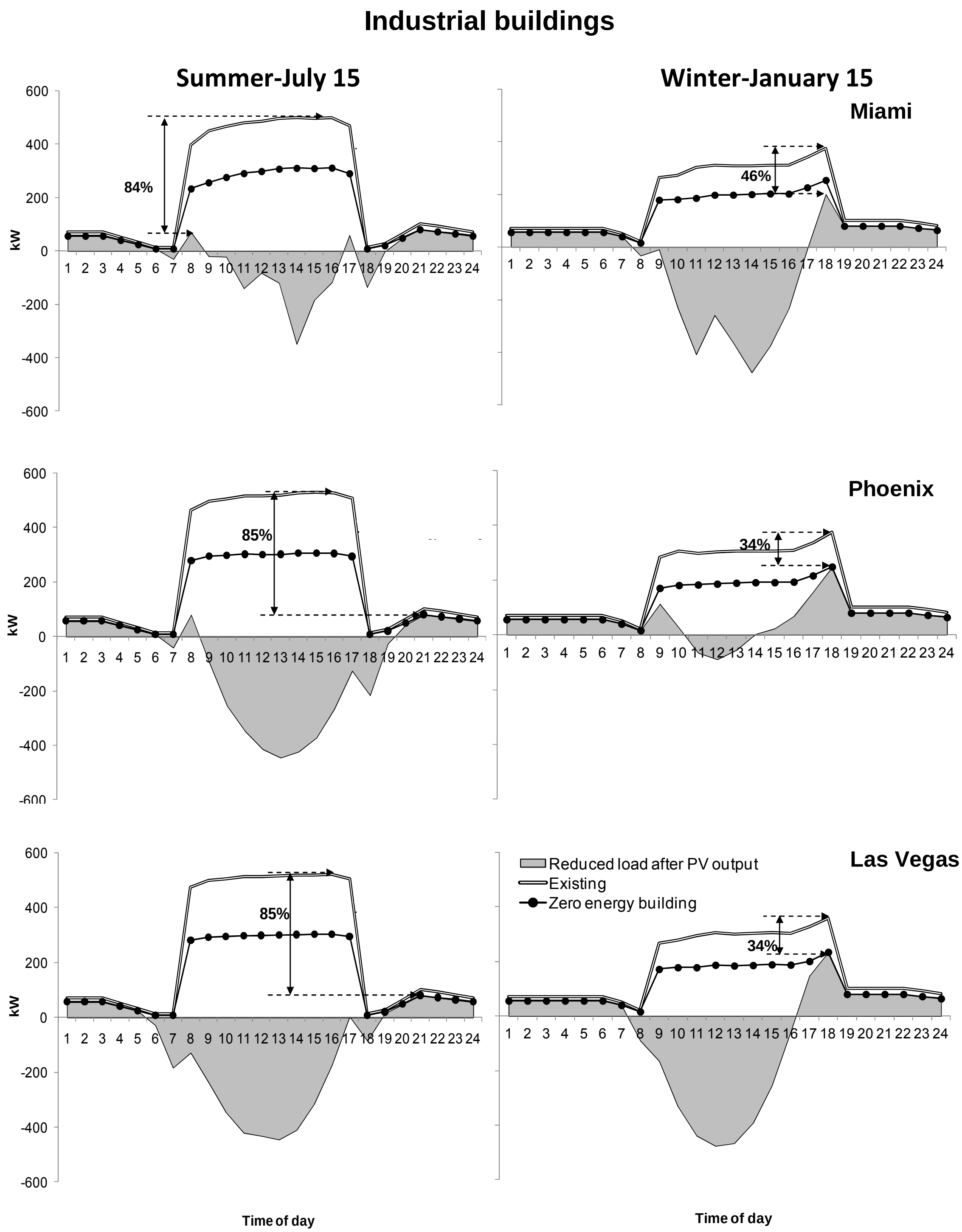


Figure 92. Examples of the potential that ZEB and PV systems have for reducing summer and winter peak electricity load demand in factory buildings located in Miami, Phoenix and Las Vegas.

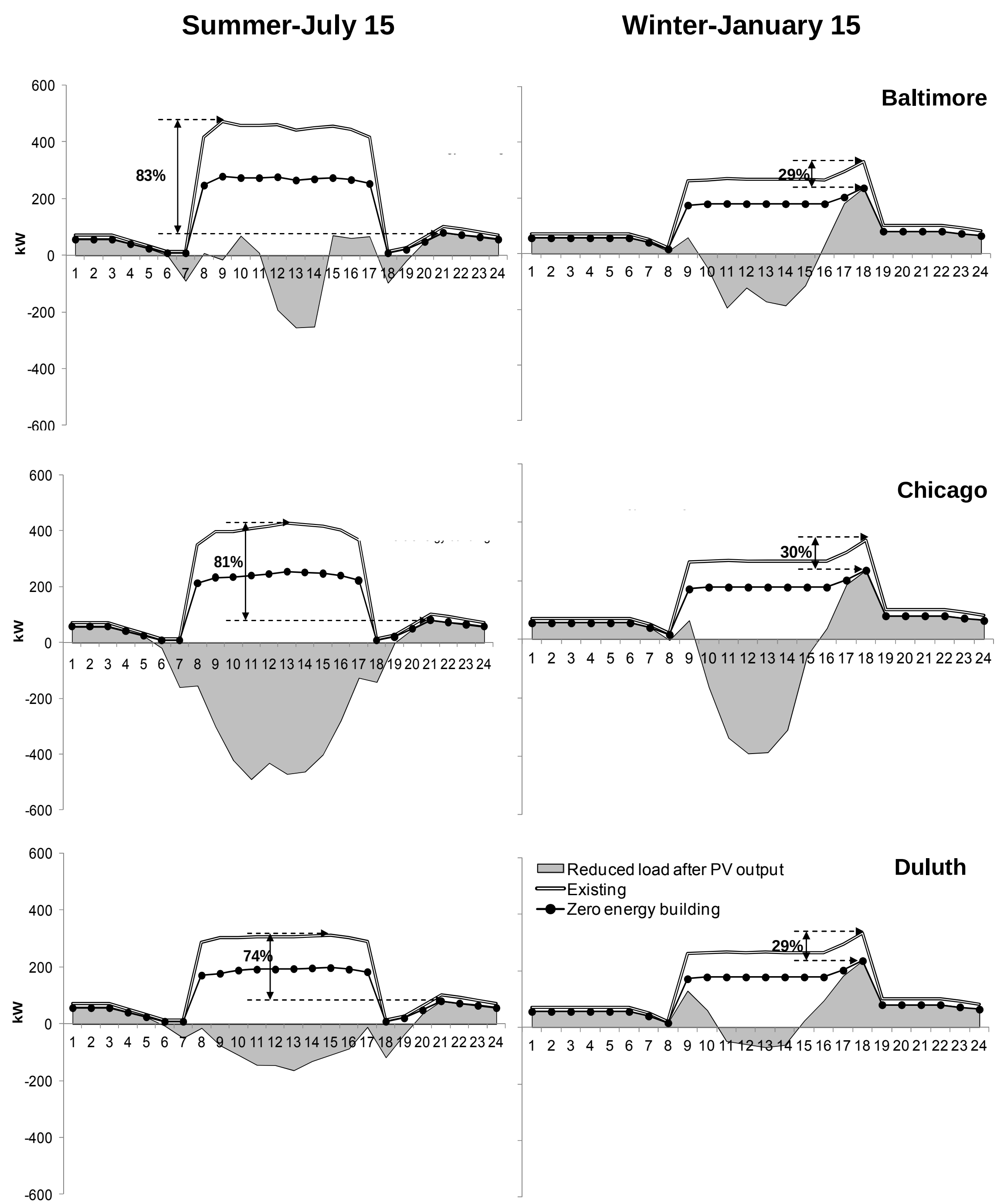


Figure 93. Examples of the potential that ZEB and PV systems have for reducing summer and winter peak electricity load demand in factory building located in Baltimore, Chicago and Duluth.

Annual peak electricity demand can also be presented using load duration curves (LDC), which display electricity demand each hour in one year (8760 hours). Hourly electricity demands were sorted in descending order of magnitude from highest demand (annual peak) to lowest demand. LCDs of residential, commercial, and industrial buildings in six cities are presented in Figure 94 - Figure 96. In each graph, two percentage numbers are shown. The smaller number represents peak electricity reduction by compliance with ASHRAE 90.1 or ASHRAE 90.2 and by installation of PV systems. The larger number represents peak electricity reduction by compliance with ASHRAE 90.1 or ASHRAE 90.2 and further application of ZEB strategy and installation of PV systems.

Peak demands in hot climates are higher than in cold climates due to the greater use of air-conditioning systems, which are used for a longer duration of months in hot weather. In residential buildings, the shorter duration of high demand for electricity can be seen from LCD graphs of cold climates, which demonstrate sudden and steep demand at the beginning of colder weather patterns. This indicates that electricity utility companies need to provide enough electricity power to satisfy demands that occur in only short periods of time. In commercial and industrial buildings where electricity is also used heavily in other systems, such as lighting and appliances, the sudden sharp rise in demand is not obvious in a cold climate's LCD graphs.

ASHRAE-compliant buildings with typical size PV systems can reduce electricity peak demand compared with existing buildings at 46% to 58% in small houses, 17% to 23% in medium office buildings, and 30% to 42% in factory buildings. With the ZEB strategy and typical PV systems, the electricity peak reduction percentages compared with existing buildings were 58% to 65% in small houses, 37% to 42% in medium office buildings, and 47% to 52% in factory buildings. The percentage increases with colder climates and the proportion of PV system size-to-building electricity loads. However, a higher proportion of PV system size-to-building electricity loads also results in more excess electricity sold back to the electric grids, which can be used to reduce electric utility companies' overall peak demand. This positive effect will turn to a negative effect when the penetration of PV systems is high in the future.

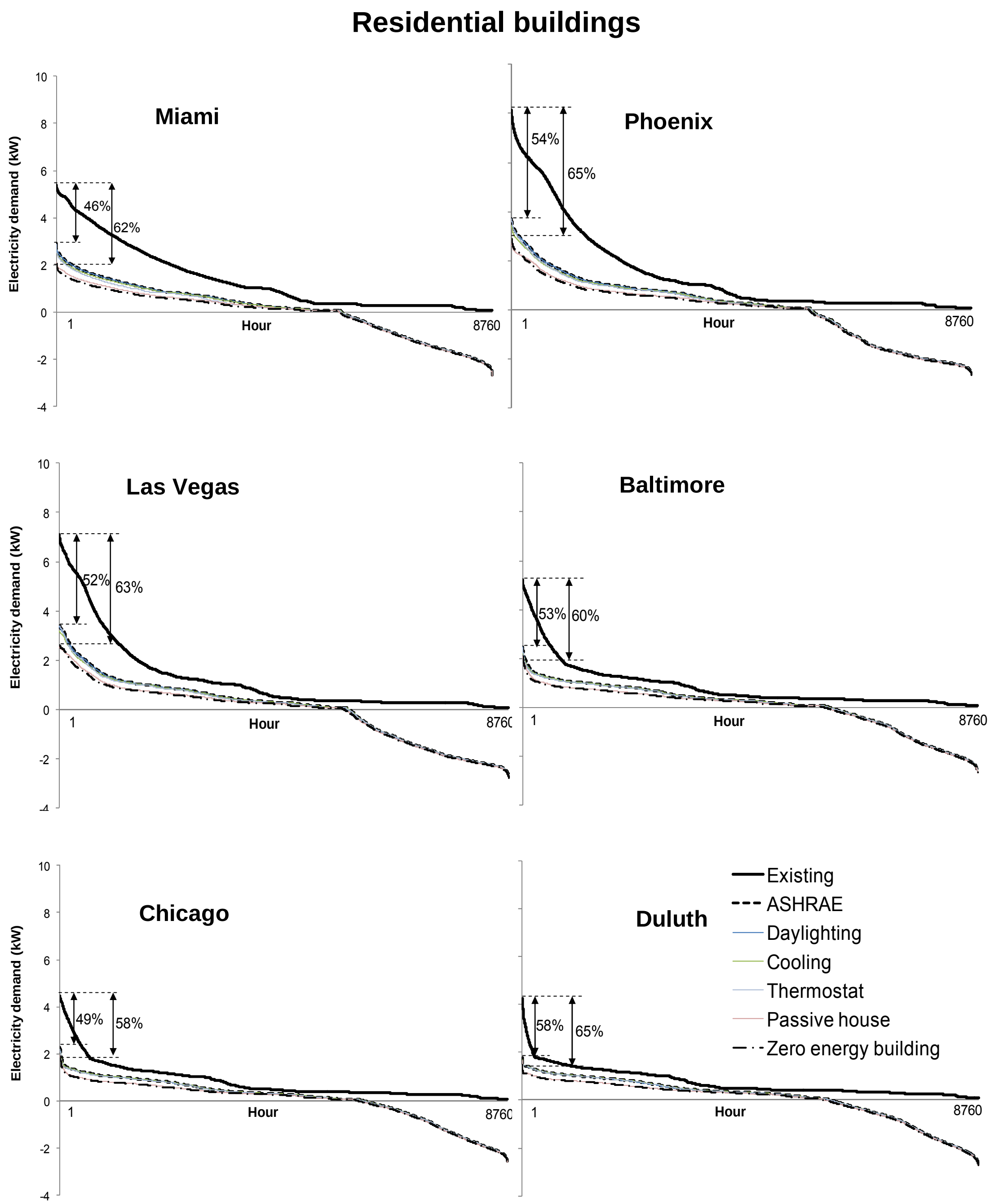


Figure 94. Comparison of load duration curves from existing small houses with load duration curves after each energy efficiency design strategy and PV systems were applied in six cities.

Commercial buildings

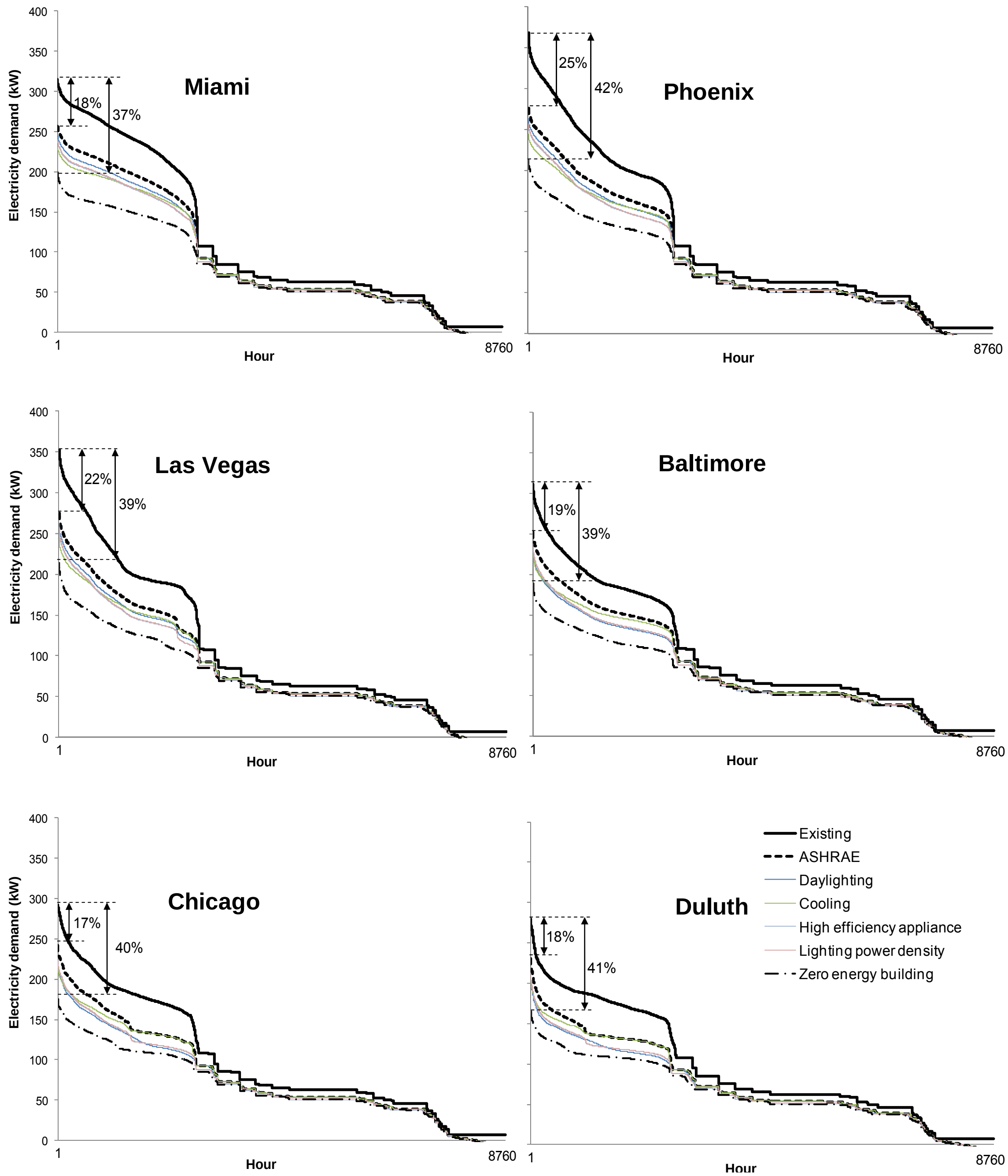


Figure 95. Comparison of load duration curves from existing medium office buildings with load duration curves after each energy efficiency design strategy and PV systems were applied in six cities.

Industrial buildings

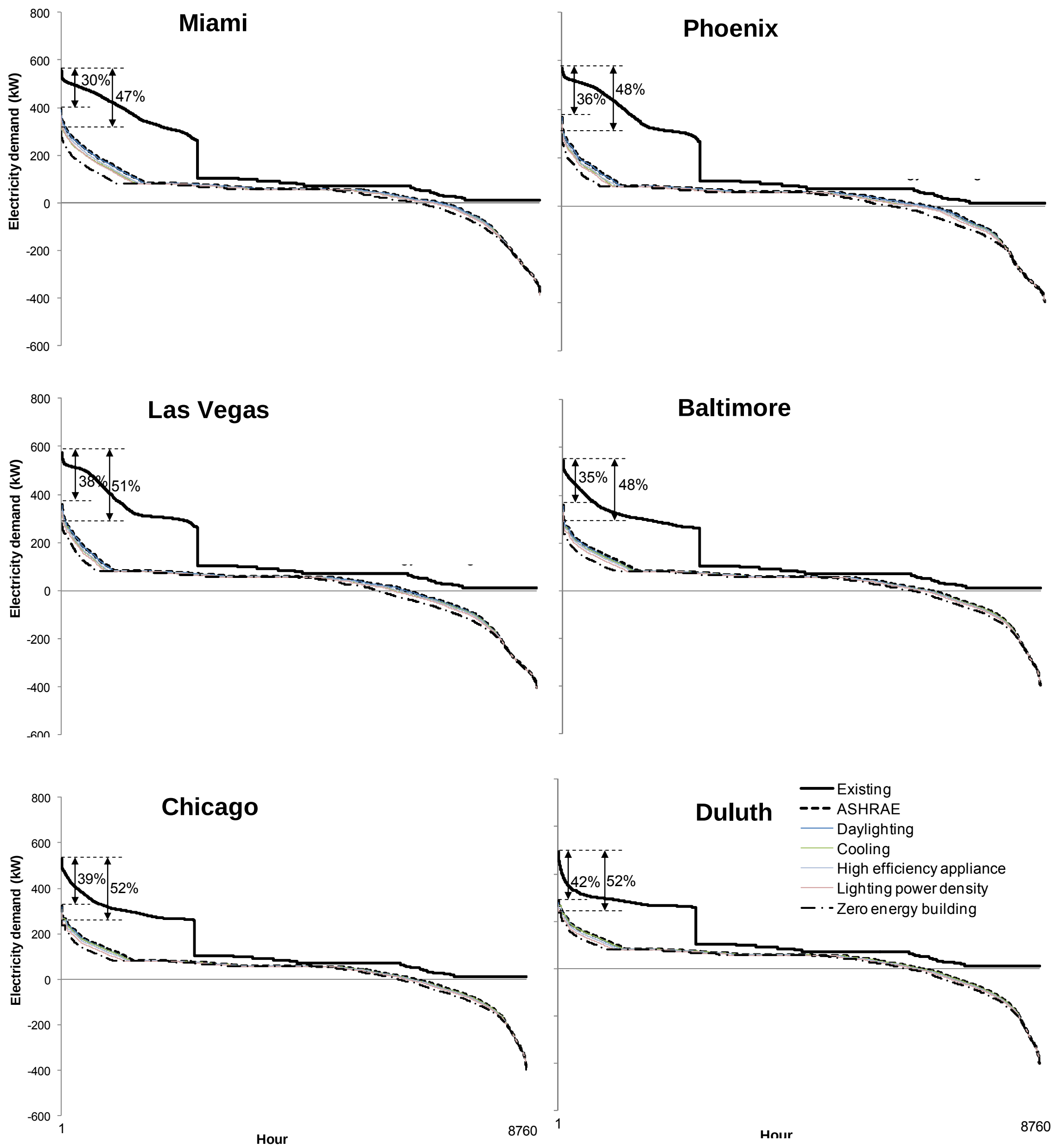


Figure 96. Comparison of load duration curves from existing factory buildings with load duration curves after each energy efficiency design strategy and PV systems were applied in six cities.

Table 26 - Table 28 show peak electricity demand from each case in six cities in residential buildings, commercial buildings, and industrial buildings presented in Figure 94 - Figure 96. With a typical PV system size, in small houses, ASHRAE-compliant buildings can further reduce peak electricity 3% to 9%. The percentages become higher when the climate gets colder. For medium office buildings, peak electricity demand can be further reduced 3% to 5% and does not vary with colder climates. In factory buildings, peak electricity demand can be further reduced 10% to 20%. The percentage becomes higher when the climate gets colder. The peak reduction percentage when PV systems were added in the buildings with ZEB strategies also followed the same trend as ASHRAE-compliant with PV systems buildings, but the reduction percentages are less.

Table 26. Residential buildings' peak loads in six cities when energy efficiency design strategies were applied, with and without PV electricity output.

Small house			Existing	ASHRAE	Wall insulation	Roof insulation	Glazing	Wall, roof, glazing	Daylighting	Thermal Mass	Cooling	Heating	LPD	High efficiency appliance	Thermostat	Passive house	Zero energy building
Miami	Without PV	kW	5.4	3.1	2.7	3.1	3.0	2.6	3.0	3.0	2.9	3.1	2.9	3.0	3.0	2.3	2.2
		%	100%	57%	49%	57%	57%	49%	56%	56%	54%	57%	53%	55%	56%	42%	41%
	With 4 kW PV	kW	5.4	2.9	2.5	2.9	2.9	2.4	2.9	2.8	2.7	2.9	2.7	2.8	2.9	2.1	2.0
		%	100%	54%	46%	54%	53%	45%	53%	52%	50%	54%	50%	51%	53%	39%	38%
Phoenix	Without PV	kW	8.1	4.0	3.4	4.0	3.8	3.3	3.9	3.9	3.7	4.0	3.7	3.9	4.0	3.0	3.1
		%	100%	49%	42%	49%	47%	40%	48%	48%	45%	49%	46%	48%	49%	36%	38%
	With 4 kW PV	kW	8.1	3.7	3.2	3.7	3.6	3.0	3.7	3.6	3.4	3.7	3.5	3.6	3.7	2.7	2.9
		%	100%	46%	39%	46%	44%	37%	46%	45%	42%	46%	43%	45%	46%	33%	35%
Las Vegas	Without PV	kW	7.1	3.6	3.1	3.6	3.5	3.0	3.5	3.6	3.4	3.6	3.5	3.5	3.6	2.7	2.8
		%	100%	51%	44%	51%	50%	43%	49%	50%	47%	51%	49%	49%	51%	38%	39%
	With 4 kW PV	kW	7.1	3.4	2.9	3.4	3.3	2.9	3.4	3.4	3.2	3.4	3.2	3.3	3.4	2.5	2.6
		%	100%	48%	41%	48%	47%	40%	48%	47%	45%	48%	45%	46%	48%	36%	37%
Baltimore	Without PV	kW	5.2	2.7	2.6	2.7	2.6	2.5	2.6	2.6	2.5	2.7	2.5	2.6	2.6	2.2	2.3
		%	100%	51%	50%	51%	49%	49%	49%	50%	48%	51%	49%	49%	50%	43%	44%
	With 4 kW PV	kW	5.2	2.5	2.4	2.5	2.4	2.3	2.5	2.4	2.3	2.5	2.3	2.4	2.4	2.1	2.1
		%	100%	47%	46%	47%	45%	44%	47%	46%	44%	47%	44%	46%	47%	39%	40%
Chicago	Without PV	kW	4.5	2.5	2.5	2.5	2.4	2.4	2.4	2.5	2.4	2.5	2.4	2.4	2.5	2.1	2.1
		%	100%	56%	55%	56%	55%	54%	54%	55%	53%	56%	52%	54%	56%	48%	47%
	With 4 kW PV	kW	4.5	2.3	2.2	2.3	2.2	2.1	2.2	2.2	2.1	2.3	2.0	2.2	2.2	2.0	1.9
		%	100%	51%	49%	51%	48%	47%	48%	49%	48%	51%	46%	48%	49%	44%	42%
Duluth	Without PV	kW	4.2	2.2	2.2	2.2	2.0	2.0	2.0	2.1	2.1	2.2	1.9	2.1	2.0	2.0	1.9
		%	100%	51%	51%	51%	48%	48%	47%	49%	49%	51%	45%	48%	47%	48%	44%
	With 4 kW PV	kW	4.2	1.8	1.8	1.8	1.7	1.7	1.6	1.7	1.7	1.8	1.5	1.7	1.6	1.7	1.5
		%	100%	42%	42%	42%	40%	39%	39%	41%	40%	42%	36%	40%	39%	39%	35%

Table 27. Commercial buildings' peak loads in six cities when energy efficiency design strategies were applied, with and without PV electricity output.

Medium office			Existing	ASHRAE	Wall insulation	Roof insulation	Glazing	Wall, roof, glazing	Daylighting	Thermal mass	Cooling	Heating	Desk temp. reset	Thermostat setting	High efficiency appliance	Lighting power density	Zero energy building
Miami	Without PV	kW	314.4	267.4	265.2	265.2	267.9	264.3	254.6	259.9	237.9	267.4	267.4	260.7	248.5	249.3	204.2
		%	100%	85%	84%	84%	85%	84%	81%	83%	76%	85%	85%	83%	79%	79%	65%
	With 30 kW PV	kW	314.4	256.3	255.4	256.0	257.7	255.8	248.9	249.3	230.3	256.3	256.3	254.4	239.0	239.7	198.8
		%	100%	82%	81%	81%	82%	81%	79%	79%	73%	82%	82%	81%	76%	76%	63%
Phoenix	Without PV	kW	369.0	294.7	291.1	294.2	299.6	293.4	281.2	287.4	259.8	294.7	294.7	291.3	275.2	275.7	220.6
		%	100%	80%	79%	80%	81%	80%	76%	78%	70%	80%	80%	79%	75%	75%	60%
	With 30 kW PV	kW	369.0	276.1	272.2	275.5	281.4	276.3	263.2	268.9	244.1	276.1	276.2	273.8	256.5	257.1	212.3
		%	100%	75%	74%	75%	76%	75%	71%	73%	66%	75%	75%	74%	70%	70%	58%
Las Vegas	Without PV	kW	352.1	286.2	284.1	286.0	291.6	289.4	273.5	275.9	254.7	286.2	286.2	285.5	266.9	267.4	225.1
		%	100%	81%	81%	81%	83%	82%	78%	78%	72%	81%	81%	81%	76%	76%	64%
	With 30 kW PV	kW	352.1	275.3	273.2	275.0	280.7	278.4	262.6	260.6	243.8	275.3	275.3	274.5	256.0	256.5	214.1
		%	100%	78%	78%	78%	80%	79%	75%	74%	69%	78%	78%	78%	73%	73%	61%
Baltimore	Without PV	kW	311.3	261.1	260.9	259.6	256.1	253.7	238.0	260.2	232.1	261.1	261.6	256.9	242.2	242.9	193.9
		%	100%	84%	84%	83%	82%	82%	76%	84%	75%	84%	84%	83%	78%	78%	62%
	With 30 kW PV	kW	311.3	251.6	251.0	251.4	248.2	246.9	233.8	249.4	227.3	251.6	251.6	244.5	233.1	234.0	189.0
		%	100%	81%	81%	81%	80%	79%	75%	80%	73%	81%	81%	79%	75%	75%	61%
Chicago	Without PV	kW	291.9	250.4	251.1	250.3	244.4	240.3	227.2	248.9	226.4	250.4	250.6	243.9	230.5	232.1	185.0
		%	100%	86%	86%	86%	84%	82%	78%	85%	78%	86%	86%	84%	79%	79%	63%
	With 30 kW PV	kW	291.9	241.7	242.4	241.5	235.3	229.8	223.3	236.3	217.6	241.7	241.8	233.1	221.7	223.3	175.1
		%	100%	83%	83%	83%	81%	79%	76%	81%	75%	83%	83%	80%	76%	76%	60%
Duluth	Without PV	kW	279.8	239.6	241.6	239.7	230.7	225.2	217.1	237.4	217.5	239.6	240.0	232.2	220.2	221.8	175.1
		%	100%	86%	86%	86%	82%	80%	78%	85%	78%	86%	86%	83%	79%	79%	63%
	With 30 kW PV	kW	279.8	230.4	232.4	230.5	219.3	212.2	210.9	224.4	208.4	230.4	230.9	221.5	211.1	212.7	165.7
		%	100%	82%	83%	82%	78%	76%	75%	80%	74%	82%	82%	79%	75%	76%	59%

Table 28. Industrial buildings' peak loads in six cities when energy efficiency design strategies were applied, with and without PV electricity output.

Factory			Existing	ASHRAE	Wall insulation	Roof insulation	Glazing	Wall, roof, glazing	Daylighting	Thermal mass	Cooling	Heating	Desk temp. reset	Thermostat setting	High efficiency appliance	Lighting power density	Zero energy building
Miami	Without PV	kW	562.3	466.0	466.3	465.5	465.9	465.5	463.1	422.6	418.4	466.0	465.9	457.0	448.9	434.9	370.8
		%	100%	83%	83%	83%	83%	83%	82%	75%	74%	83%	83%	81%	80%	77%	66%
	With 500 kW PV	kW	562.3	393.8	393.0	393.9	394.5	395.8	389.2	359.0	347.5	393.8	394.0	384.4	376.2	364.4	298.3
		%	100%	70%	70%	70%	70%	70%	69%	64%	62%	70%	70%	68%	67%	65%	53%
Phoenix	Without PV	kW	568.6	424.4	423.9	424.3	424.5	424.5	420.8	420.1	385.9	424.4	424.4	424.4	406.5	391.6	344.3
		%	100%	75%	75%	75%	75%	75%	74%	74%	68%	75%	75%	75%	71%	69%	61%
	With 500 kW PV	kW	568.6	365.2	362.5	364.9	365.4	365.3	364.4	349.3	342.5	365.2	365.3	353.5	350.0	336.3	295.0
		%	100%	64%	64%	64%	64%	64%	64%	61%	60%	64%	64%	62%	62%	59%	52%
Las Vegas	Without PV	kW	575.5	429.2	429.1	429.2	429.3	429.1	426.6	408.4	389.5	429.2	429.2	429.2	411.5	396.9	348.4
		%	100%	75%	75%	75%	75%	75%	74%	71%	68%	75%	75%	75%	72%	69%	61%
	With 500 kW PV	kW	575.5	357.4	356.7	357.4	357.5	356.8	355.3	339.3	323.8	357.4	356.3	357.8	340.0	325.5	280.4
		%	100%	62%	62%	62%	62%	62%	62%	59%	56%	62%	62%	62%	59%	57%	49%
Baltimore	Without PV	kW	544.1	415.9	415.8	415.8	415.7	415.6	409.0	407.5	379.1	415.9	415.9	416.5	398.6	386.1	345.6
		%	100%	76%	76%	76%	76%	76%	75%	75%	70%	76%	76%	77%	73%	71%	64%
	With 500 kW PV	kW	544.1	356.2	356.1	356.2	356.1	356.0	353.6	348.0	320.4	356.2	356.2	356.2	338.9	326.4	285.2
		%	100%	65%	65%	65%	65%	65%	65%	64%	59%	65%	65%	65%	62%	60%	52%
Chicago	Without PV	kW	528.4	399.0	398.9	399.0	399.2	399.2	391.0	394.1	366.3	399.0	398.9	403.5	382.0	370.2	331.4
		%	100%	76%	75%	76%	76%	76%	74%	75%	69%	76%	75%	76%	72%	70%	63%
	With 500 kW PV	kW	528.4	321.2	321.4	321.1	318.6	318.7	319.7	308.9	305.7	321.2	322.5	310.1	306.0	292.1	256.2
		%	100%	61%	61%	61%	60%	60%	61%	58%	58%	61%	61%	59%	58%	55%	48%
Duluth	Without PV	kW	493.9	387.4	386.6	387.1	383.9	382.9	376.3	372.7	356.6	387.4	385.1	379.2	371.9	358.6	309.0
		%	100%	78%	78%	78%	78%	78%	76%	75%	72%	78%	78%	77%	75%	73%	63%
	With 500 kW PV	kW	493.9	285.7	284.6	285.4	281.2	280.2	279.9	272.1	265.4	285.7	284.2	275.3	270.1	255.9	235.7
		%	100%	58%	58%	58%	57%	57%	57%	55%	54%	58%	58%	56%	55%	52%	48%

Impact of building use schedule on peak electricity demand: Peak electricity demand in buildings with typical schedules compared to buildings with high use or 24-hour use schedules in Chicago are shown in Figure 97 - Figure 99. Detailed data for all six types of buildings are shown in Table 29 - Table 31.

In residential buildings, 24-hour use schedule buildings can benefit more from applying energy efficiency design strategies and installing PV systems because the buildings are used more during the day. In commercial and industrial buildings, 24-hour use buildings have a negative impact on peak electricity demand reduction percentages because the buildings are used more at night time. The proportion of peak electricity produced from PV system decreases because the PV electricity output is constant.

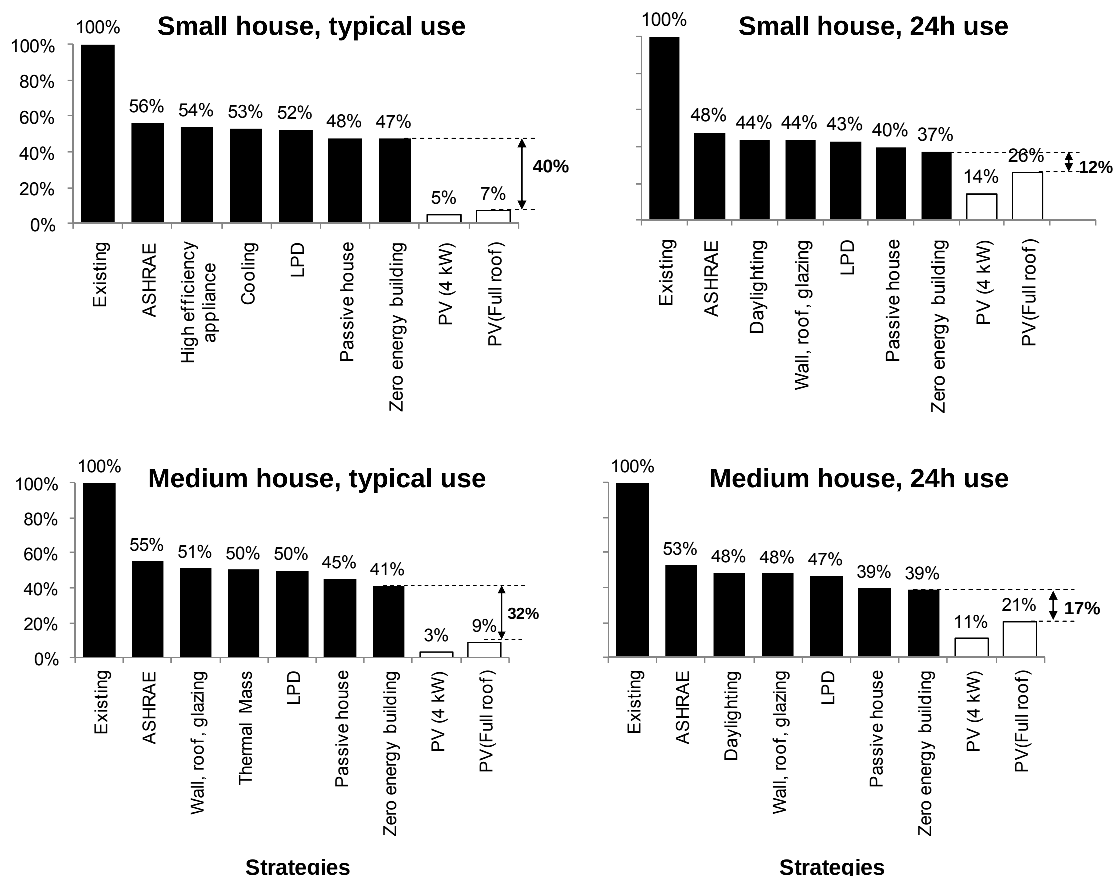


Figure 97. Comparison of peak electricity demand between typical use schedule and 24-hour use schedule residential buildings in Chicago.

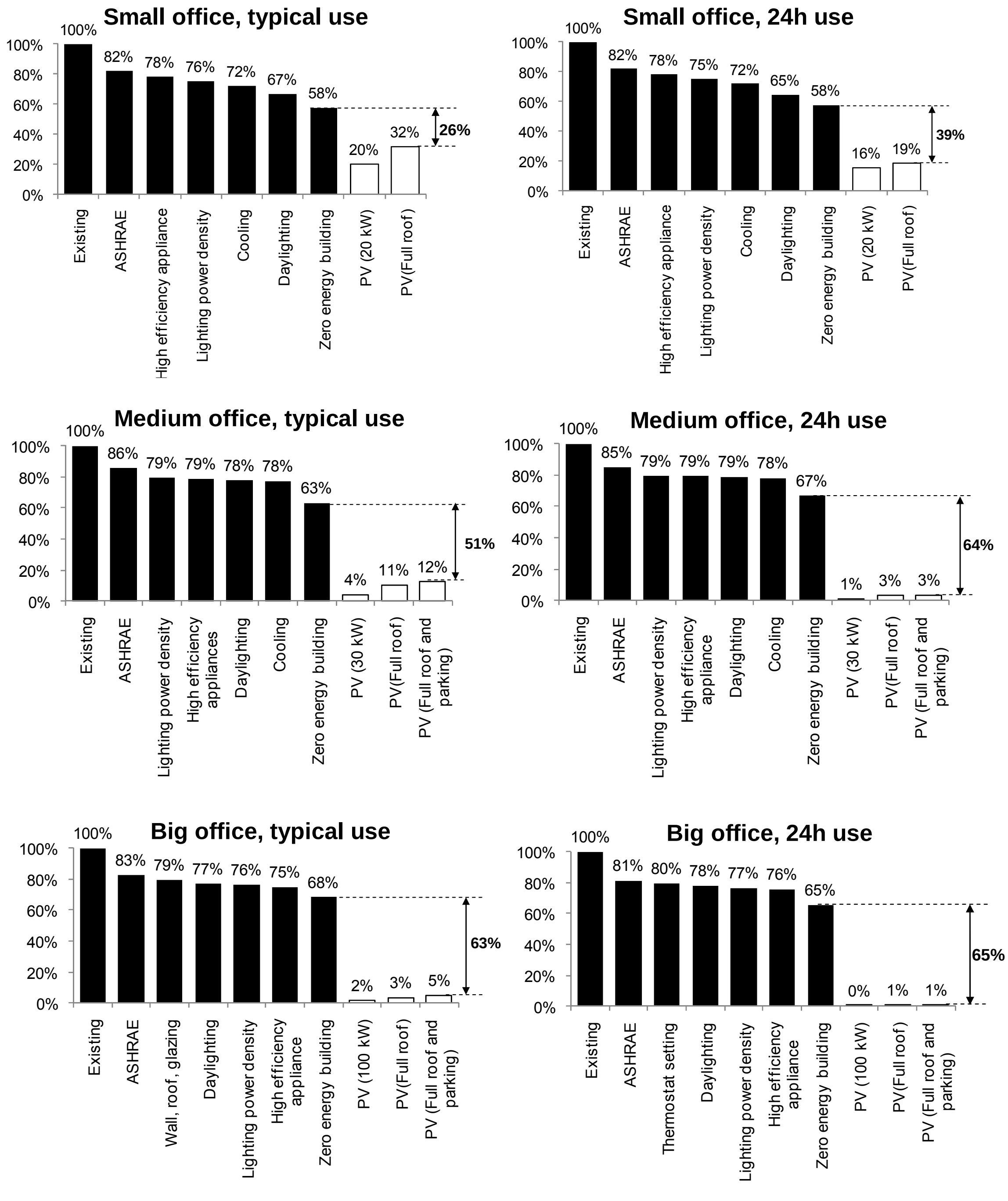


Figure 98. Comparison of peak electricity demand between typical use schedule and 24-hour use schedule commercial buildings in Chicago.

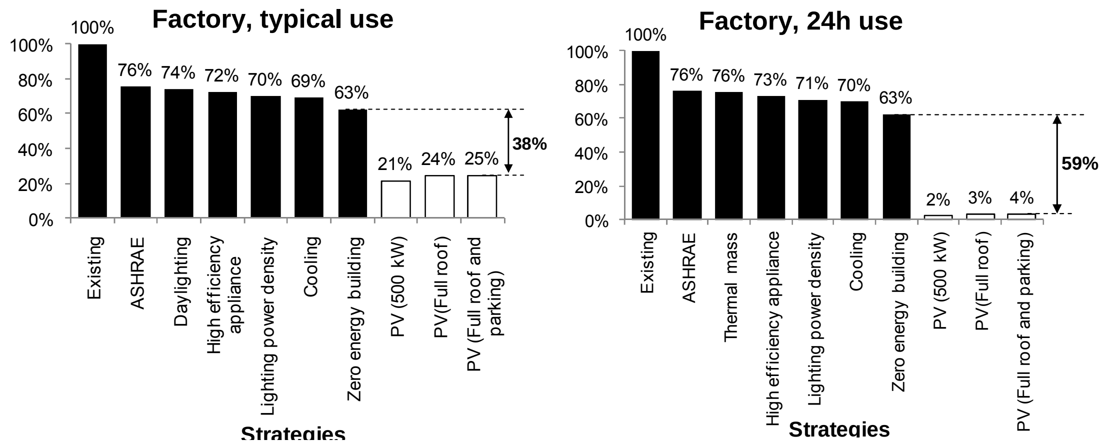


Figure 99. Comparison of peak electricity demand between typical use schedule and 24-hour use schedule industrial buildings in Chicago.

Table 29. Comparison of peak electricity demand between typical use schedule and 24-hour use schedule residential buildings in Chicago.

Strategies	Small house				Medium house			
	Typical use		24h use		Typical use		24h use	
	kW	%	kW	%	kW	%	kW	%
Existing	4.48	100%	5.29	100%	8.25	100%	8.73	100%
ASHRAE	2.51	56%	2.53	48%	4.54	55%	4.61	53%
Wall insulation	2.47	55%	2.43	46%	4.42	54%	4.40	50%
Roof insulation	2.51	56%	2.53	48%	4.54	55%	4.61	53%
Glazing	2.45	55%	2.41	46%	4.31	52%	4.34	50%
Wall, roof, glazing	2.43	54%	2.31	44%	4.22	51%	4.18	48%
Daylighting	2.41	54%	2.32	44%	4.23	51%	4.22	48%
Thermal Mass	2.48	55%	2.46	47%	4.15	50%	4.28	49%
Cooling	2.37	53%	2.38	45%	4.32	52%	4.37	50%
Heating	2.51	56%	2.53	48%	4.54	55%	4.61	53%
LPD	**2.35**	**52%**	**2.27**	**43%**	**4.13**	**50%**	**4.09**	**47%**
High efficiency appliance	2.41	54%	2.41	46%	4.28	52%	4.37	50%
Thermostat	2.50	56%	2.41	46%	4.48	54%	4.46	51%
Passive house	**2.13**	**48%**	**2.10**	**40%**	**3.74**	**45%**	**3.45**	**39%**
Zero energy building	**2.13**	**47%**	**1.97**	**37%**	**3.40**	**41%**	**3.38**	**39%**

Table 30. Comparison of peak electricity demand between typical use schedule and 24-hour use schedule commercial buildings in Chicago.

Strategies	Small office				Medium office				Big office			
	Typical use		24h use		Typical use		24h use		Typical use		24h use	
	kW	%	kW	%	kW	%	kW	%	kW	%	kW	%
Existing	23.89	100%	24.10	100%	291.92	100%	325.49	100%	2,489.78	100%	2,845.05	100%
ASHRAE	19.59	82%	19.73	82%	250.43	86%	276.55	85%	2,057.30	83%	2,315.78	81%
Wall insulation	19.45	81%	19.60	81%	251.12	86%	276.01	85%	2,061.96	83%	2,310.91	81%
Roof insulation	19.56	82%	19.69	82%	250.29	86%	274.90	84%	2,056.28	83%	2,312.18	81%
Glazing	19.00	80%	19.17	80%	244.35	84%	274.32	84%	2,007.87	81%	2,302.62	81%
Wall, roof, glazing	18.82	79%	18.96	79%	240.35	82%	270.96	83%	1,978.69	79%	2,290.69	81%
Daylighting	**15.96**	**67%**	**15.58**	**65%**	227.22	78%	257.21	79%	1,915.16	77%	2,222.11	78%
Thermal mass	19.33	81%	19.20	80%	248.90	85%	276.21	85%	2,014.19	81%	2,298.99	81%
Cooling	17.22	72%	17.33	72%	**226.40**	**78%**	**254.45**	**78%**	2,038.81	82%	2,300.50	81%
Heating	19.59	82%	19.73	82%	250.43	86%	276.55	85%	2,057.30	83%	2,315.78	81%
Desk temp. reset	-	-	-	-	250.60	86%	276.88	85%	2,054.58	83%	2,321.00	82%
Thermostat setting	19.17	80%	19.37	80%	243.89	84%	271.42	83%	1,983.70	80%	2,265.69	80%
High efficiency appliance	18.70	78%	18.85	78%	230.47	79%	258.58	79%	**1,865.34**	**75%**	**2,159.67**	**76%**
Lighting power density	18.04	76%	18.19	75%	232.06	79%	258.64	79%	1,901.10	76%	2,180.11	77%
Zero energy building	**13.81**	**58%**	**13.92**	**58%**	**185.04**	**63%**	**217.61**	**67%**	**1,701.27**	**68%**	**1,863.10**	**65%**

Table 31. Comparison of peak electricity demand between typical use schedule and 24-hour use schedule industrial buildings in Chicago.

Strategies	Factory			
	Typical use		24h use	
	kW	%	kW	%
Existing	528.41	100%	560.28	100%
ASHRAE	398.99	76%	428.03	76%
Wall insulation	398.92	75%	427.95	76%
Roof insulation	398.98	76%	428.02	76%
Glazing	399.19	76%	427.91	76%
Wall, roof, glazing	399.23	76%	427.81	76%
Daylighting	390.96	74%	423.74	76%
Thermal mass	394.14	75%	423.31	76%
Cooling	**366.33**	**69%**	**391.84**	**70%**
Heating	398.99	76%	428.03	76%
Desk temp. reset	398.89	75%	428.03	76%
Thermostat setting	403.49	76%	426.33	76%
High efficiency appliance	381.99	72%	410.00	73%
Lighting power density	370.15	70%	398.93	71%
Zero energy building	**331.40**	**63%**	**351.29**	**63%**

3.2.3 Building electricity load met and excess electricity reduction.

In typical stand-alone PV system design, building electricity load is first determined, along with amount of load current, load voltage, and time of use. The total electricity consumption in alternate current (AC) is then converted to direct current (DC) which is the type of electricity produced from PV systems. PV system size is then determined using the DC electricity consumption calculated. The PV size should be large enough to provide electricity for building load during the design day. How the panels are connected in series and parallel is determined by building current and voltage demands. The excess electricity produced is stored in batteries, and battery size depends on storage days, site accessibility, load characteristics, and type of batteries selected.

In grid-connected PV systems, the electric grid can be used as virtual storage and thus eliminates the need for backup battery systems and lowers the overall system investment cost. The main concern with impacts from grid-connected PV systems is high output fluctuations, which can pose various risks to the electric grid system when the system penetration is high in the future. Electric grids are being transformed to smart grid systems which can handle distributed energy generators such as grid-connected PV systems better in the future. Meanwhile, many states post a limit to distributed renewable energy generation systems that can interconnect with grid systems. This limit varies from state to state. Further discussion of this topic can be found in section 3.3.1. The ideal condition for integrating grid-connected PV systems into buildings is to maximize the electricity use from the PV systems, minimize the electricity used from the electric grid, and minimize the excess electricity flowing back to the electric grid. The evaluation of energy efficiency design strategies that can increase loads met by grid-connected PV systems is examined. Over all, the preferred condition is when building electricity load that is met by PV electricity output is maximized, and excess electricity as well as electricity that is bought from the electric grid is minimized (Figure 100).

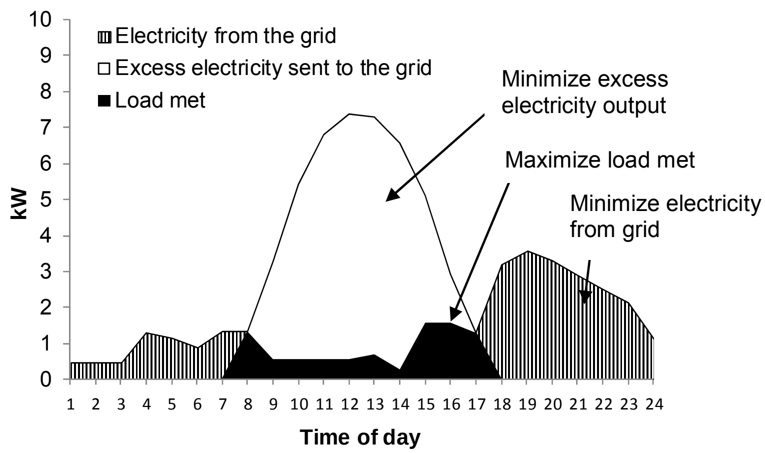


Figure 100. A schemetic graph shows electricity demand components and their targets in order to improve their efficiency.

Building electricity load that is met by PV electricity output, excess electricity power sent back to the electric grid and electricity bought from the electric grid can be calculated using equations (6), (7), and (8).

$$P_m = P_{pv} - P_{tg} \quad (6)$$

$$P_{fg} = \sum_{n=1}^{8760} \left(P_b - P_{pv}\right) \quad ; when \ \ (P_b - P_{pv}) > 0 \quad (7)$$

$$P_{tg} = \sum_{n=1}^{8760} -\left(P_b - P_{pv}\right) \quad ; when \ \ (P_b - P_{pv}) < 0 \quad (8)$$

Where

P_m = Building load power met by electricity output from PV systems (W).

P_{pv} = Electricity output power from PV systems (W).

P_{tg} = Excess electricity power sent to the electric grids (W).

P_{fg} = Electricity bought from the electric grid (W).

P_b = Building electricity load (W).

n = Hour in a year.

When applying energy efficiency design strategies, electricity demand is reduced. Load met demand is also reduced because of the overall electricity demand reduction. The overall demand reduction also results in less electricity bought from the electric grids. Excess electricity is increased because PV electricity output is constant while the demand is reduced. To evaluate the performance of energy efficiency design strategies in increasing building load met, the percentage of load met compared to overall building electricity demand is used. Excess electricity and bought electricity are shown in actual demand. Figure 101 - Figure 103 show residential, commercial, and industrial buildings load met, excess electricity, and bought electricity for varying sizes of PV systems in Miami, Baltimore, and Duluth.

In residential buildings, PV sizes used in this study were 4 kW DC and 10 kW DC. Their peak electricity outputs were equal to approximately 40% to 75% and 185% to 235% of peak electricity demand in small houses, respectively. Reducing lighting power density is the best single strategy that can increase load met percentages 2% to 3% more from 21% to 28% load met in ASHRAE-compliant buildings. Combinations of strategies, which are passive house and ZEB, can increase load met percentages approximately 3% to 6% more from ASHRAE-compliant buildings. Bigger PV systems (10 kW DC) can increase load met 7% to 11% compared with the 4 kW DC size. However, this configuration has a high impact on excess electricity consumption with an increase of approximately 8,150 kWh to 8,500 kWh, while the bought electricity consumption is decreased only about 470–820 kWh. The increased excess electricity is higher in hotter climates. Thermal mass and high efficiency appliances are two strategies that can result in the decrease of load met percentages compared with ASHRAE-compliant buildings.

In commercial buildings, PV sizes used in this study were 30 kW DC, 168 kW DC, and 225 kW DC. Their peak electricity output was equal to 10%, 50% to 60%, and 70% to 80% of peak electricity demand, respectively. Reducing lighting power density and increasing cooling system efficiency are the best single strategies for increasing load met percentages. However, the increased load met percentages are very small because of small PV system size due to limited roof area. It is less than a 1% increase from the 4% load met in ASHRAE-compliant buildings, even with the ZEB strategy. Bigger PV systems can increase the load met percentage. In this case, the 168 kW DC size and the 225 kW DC size can increase load met to 17%-19% and 23%-25%, respectively. PV size and climate have only a small impact on the amount of excess electricity produced when PV sizes are smaller than peak electricity demand and in the type of building where internal loads are dominant. Electricity bought from grid can be reduced 98-148 MWh by the ZEB strategy. The reduction in electricity demand gets smaller in colder weather and with bigger sizes of PV systems.

In industrial buildings, PV sizes used in this study were 500 kW DC and 1000 kW DC. Their peak electricity output was equal to 90% to 100% and 180% to 200% of peak electricity demand, respectively. Reducing lighting power density, increasing cooling system efficiency and thermal mass are the best single strategies that can increase load met percentages up to 2% more, from 44% to 51% load met, in ASHRAE-compliant buildings. ZEB can increase load met percentages up to 5% more than ASHRAE-compliant buildings. Bigger PV systems (1000 kW DC) in this case, reduced load met percentages. Excess electricity demand increased 500-680 MWh, and the amount of bought electricity decreased 120-300 MWh with bigger PV sizes. Climate zones have small impact on these two demands because this type of building is internal load dominant.

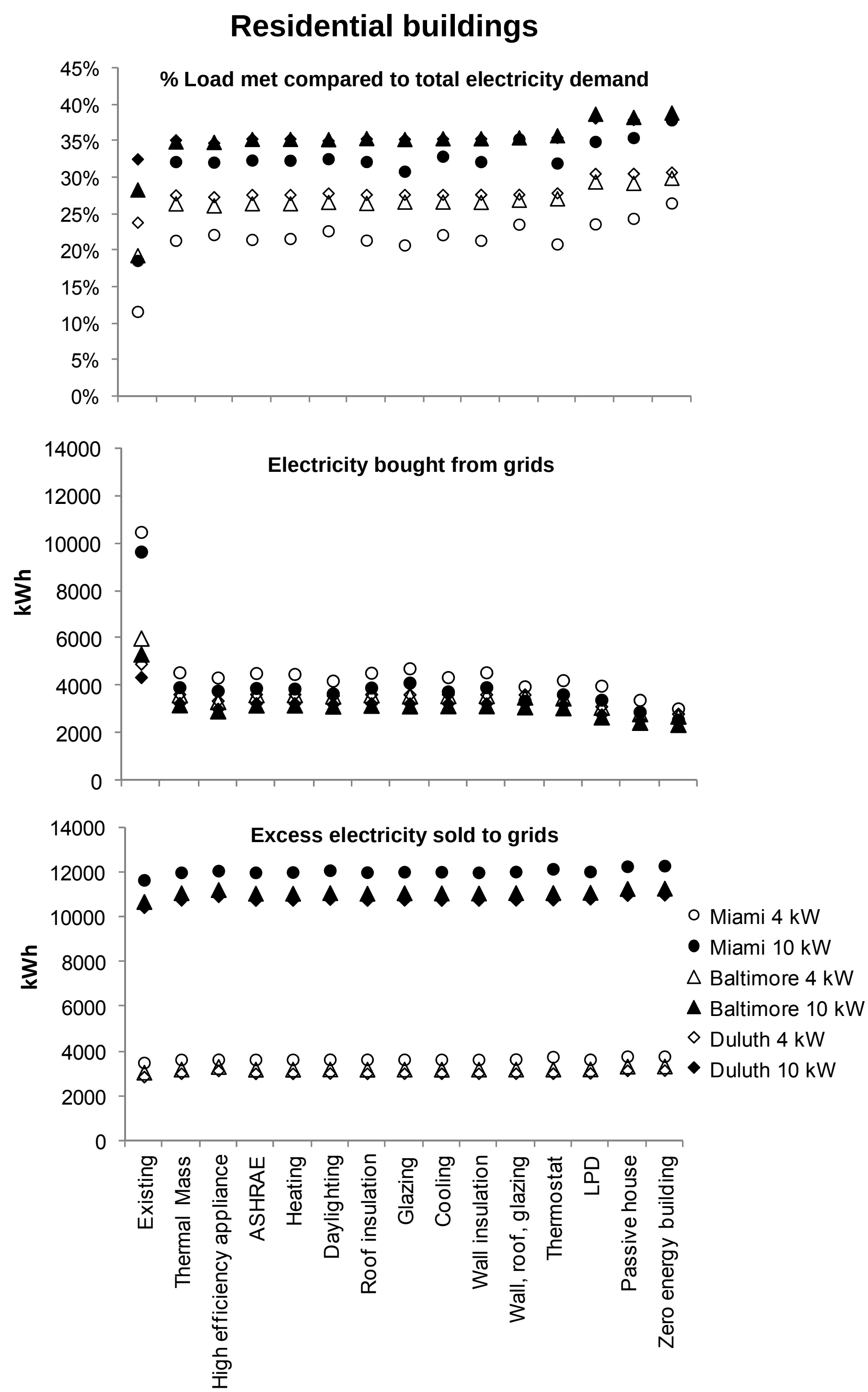


Figure 101. Comparison of building electricity load met and electricity used from the grid in residential buildings in Miami, Baltimore and Duluth.

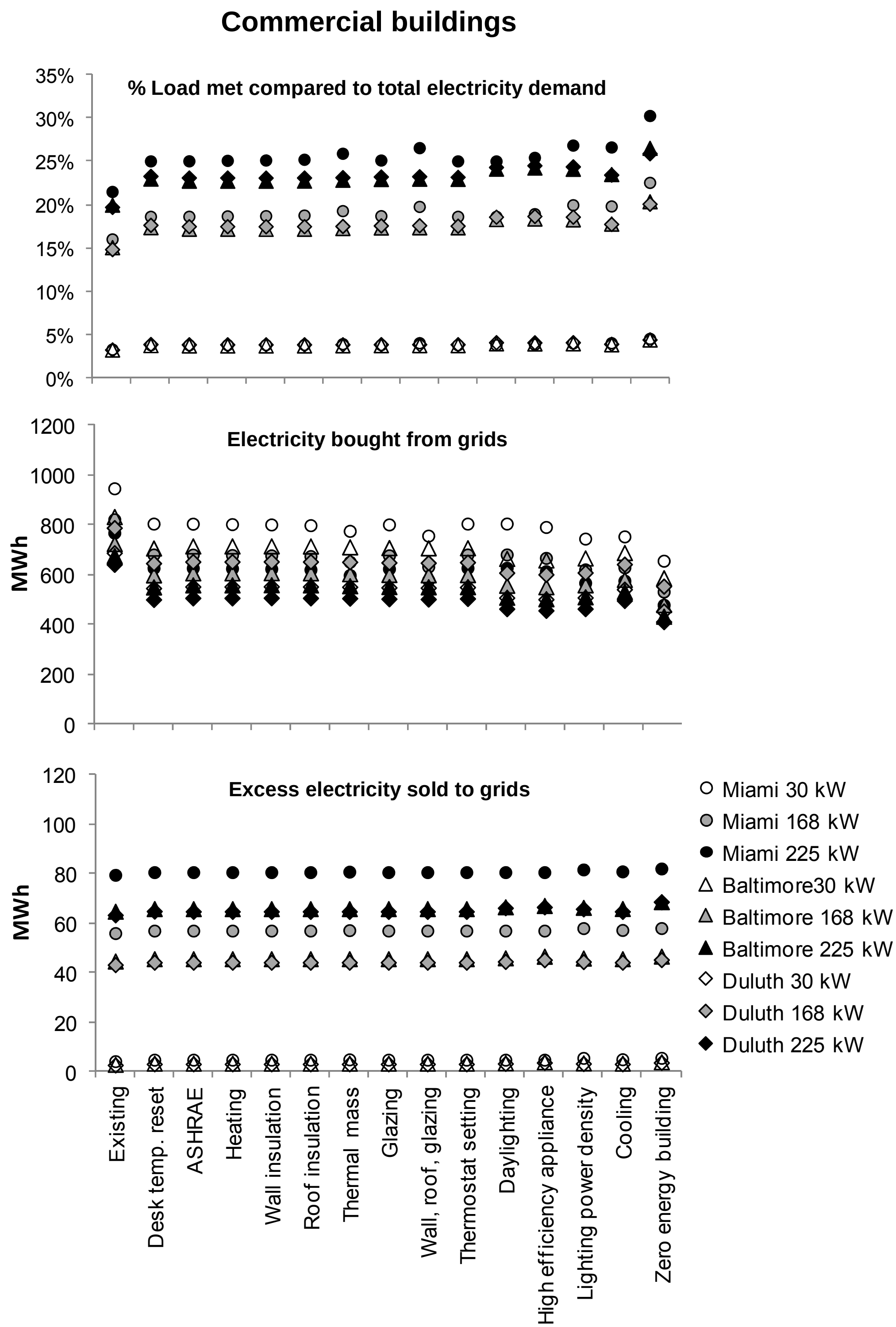


Figure 102. Comparison of building electricity load met and electricity used from the grid in commercial buildings in Miami, Baltimore, and Duluth.

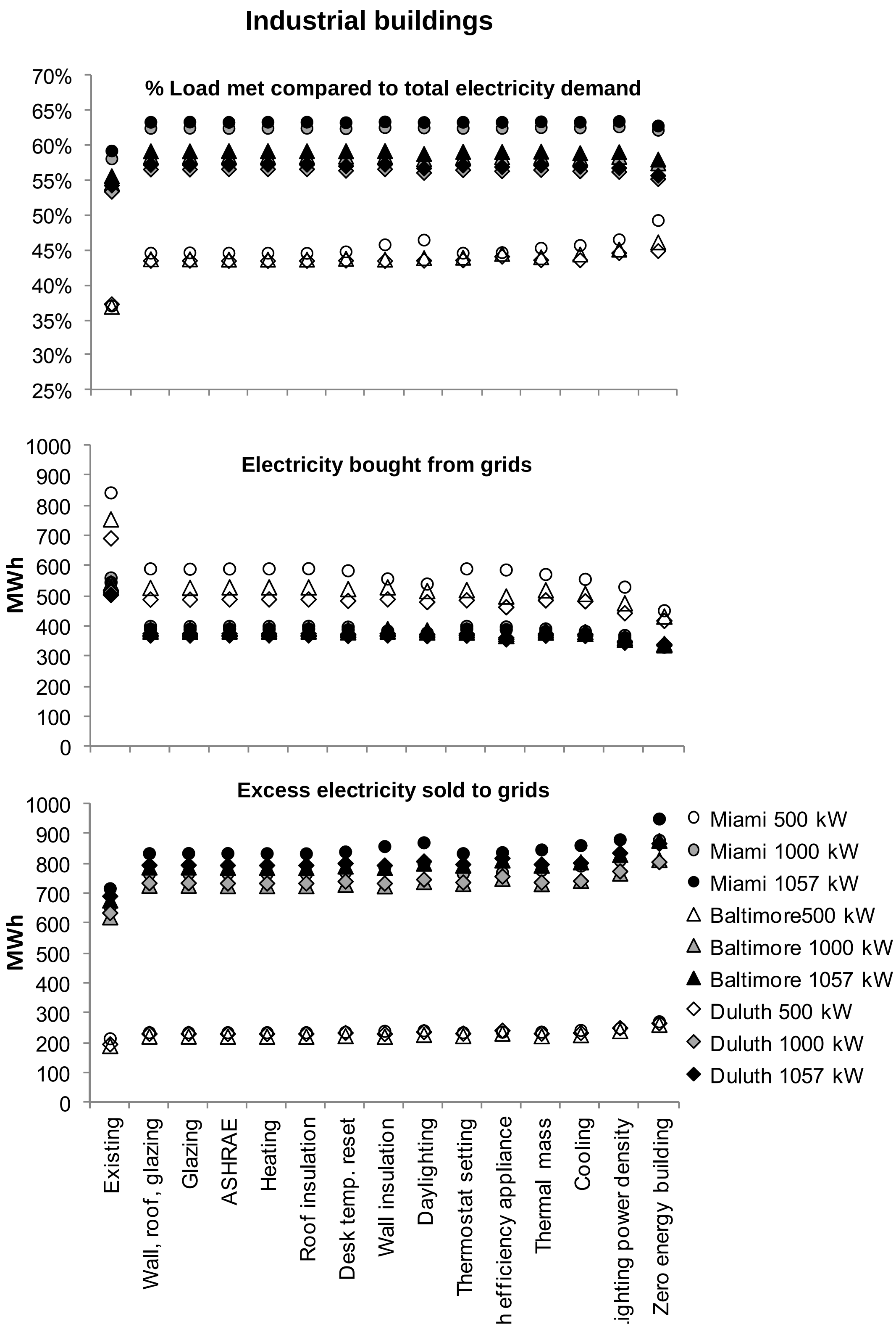


Figure 103. Comparison of building electricity load met and electricity used from the grid in industrial buildings in Miami, Baltimore, and Duluth.

3.3 Buildings with Grid-connected PV Systems and the Electric Grids

Electricity in the United States was first commercially available in 1882 in New York City. At that time, the electrical generation and distribution system invented by Thomas Edison provided 110 volts direct current (DC) to nearby customers on Broadway Street. Later, alternate current (AC) invented by Nicola Tesla was used in centralized power plants, such as the Niagara Falls hydroelectric generator that could deliver massive amounts of electricity to Buffalo more than 20 miles away. AC became more popular to use in electricity distribution systems because it was easier to transmit longer distances to reach more customers with very little loss. AC voltage can be stepped up to very high voltages using transformers. This high voltage current can be sent to customers over thinner and cheaper wires. Transformers are used again at the end of the line to step down the voltage for normal use. Although high voltage current is dangerous, its safety could be managed and the benefits outweighed the danger. At the end of nineteenth century, many small scale power plants were built in U.S. city centers.

Today, centralized large scale power plants far away from customers generate most of the electricity used. Electricity is sent to customers via grid systems, which are defined as "the network of interconnected electricity lines that transport electricity from power plants and other generating facilities to local distribution areas" (North American Electric Reliability Corporation, 2012). Electric grid systems are composed of two portions: the transmission system which delivers electricity from power plants to substations, and the distribution system delivering electricity from substations to customers (Figure 104). These electric grid systems have grown from serving small areas owned by local electricity utility companies in each city out to its suburbs, to serving long-distance interconnections between cities and regions. The systems were expanded without planning, creating highway-like patterns (Figure 105 and Figure 106).

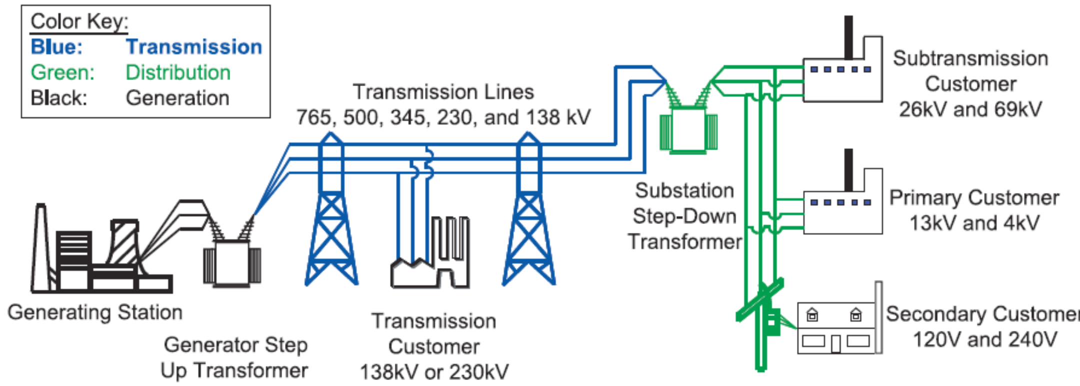


Figure 104. Electric grid transmission and distribution system diagram (U.S.-Canada Power System Outage Task Force, 2004).

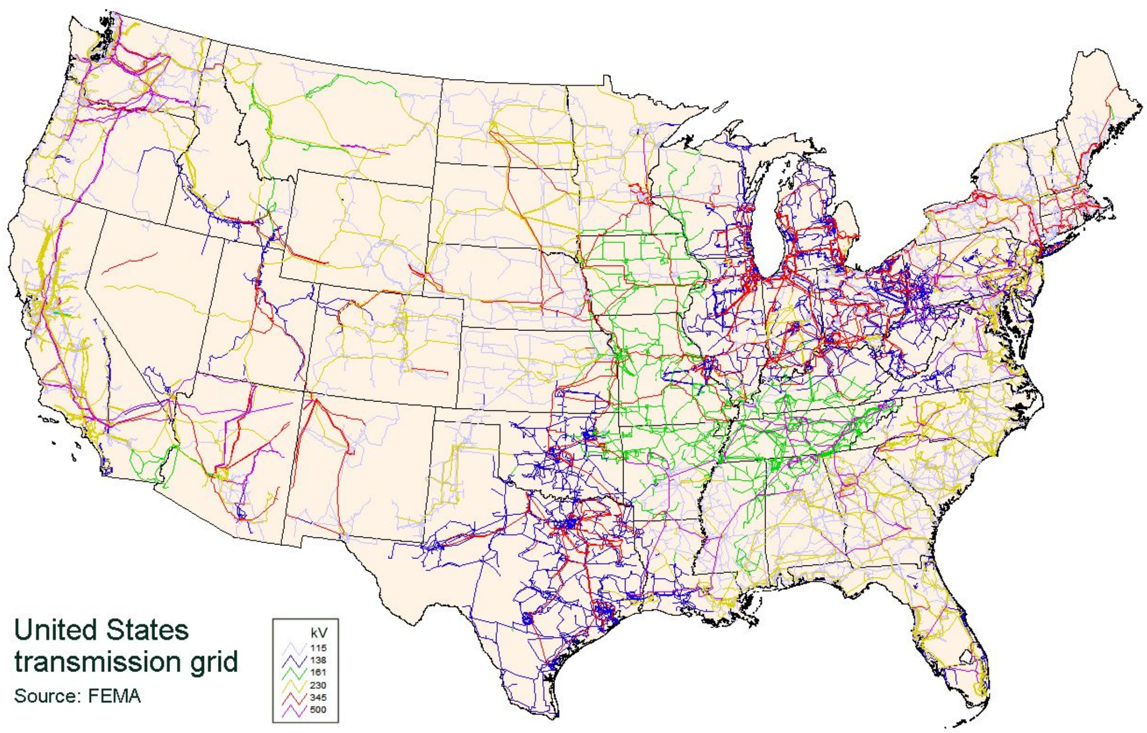


Figure 105. The United States transmission grid system (Global Energy Network Institute, 2012).

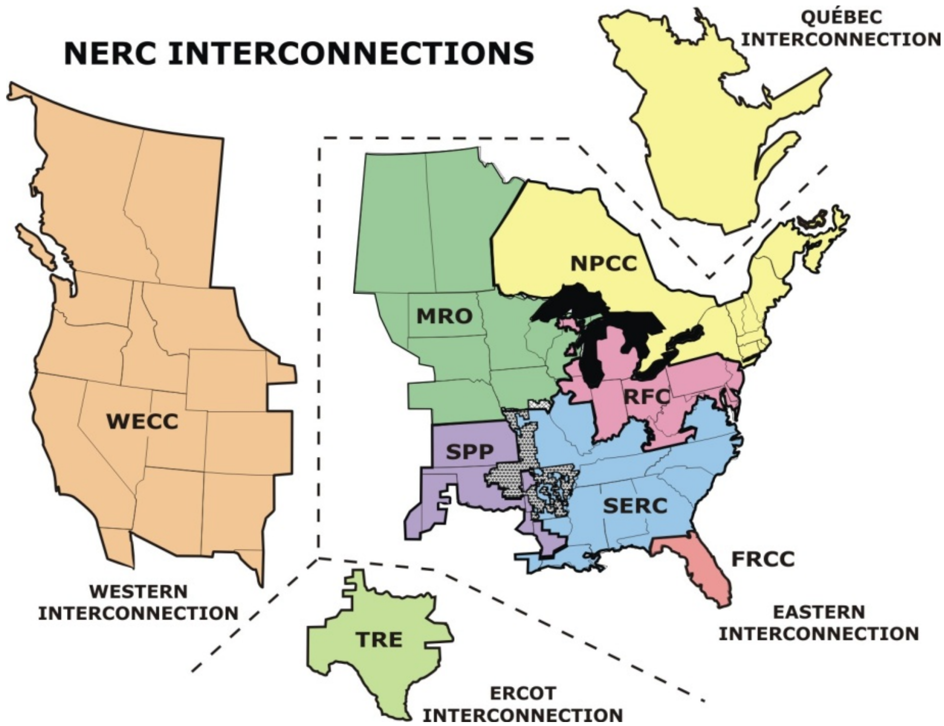


Figure 106. The main four interconnections of the North America electric power grid and the 8 electric reliability council regions (North American Electric Reliability Corporation, 2012).

Electricity is hard to store, so it is generally generated as needed. The electricity supply must be closely examined to match with demand. Moreover, electricity cannot be sent in a specific direction because it will use the path that has the least resistance. Therefore, the systems need real-time monitoring and management to ensure uninterrupted flow. The electricity generators or power plants can be divided into three categories based on function: base load power plants, load following or intermediate load power plants, and peak load power plants. The electricity demand load curve in Figure 107 represents these three kinds of loads. In addition, to be prepared for unexpected events that might increase electricity demand, electric utility companies must keep additional plants available to meet the curtain safety factor.

Base load power plants operate continuously at maximum power. They will stop or reduce work only to perform maintenance or when unexpected outages occur. These plants produce electricity at a cheap cost and must be used at their maximum capacity. They provide the minimum required amount of electricity that electric utility companies must make available to their customers at all times. Base load power plants are nuclear, geothermal, waste-to-energy, coal, biomass, and electrochemical energy storage power plants.

Intermediate load or load following power plants can be adjusted following electricity demand. They run mostly during the day and early evening when people use the most electricity. Load following power plants are not only run following the electricity demand during days and nights, they also follow variations between working days and variations among seasons. Load following power plants include hydroelectric power plants and steam turbine power plants that run on natural gas or heavy fuel oil.

Peak load power plants operate only during times of peak demand. In regions with heavy air conditioning use, the summer peak demand times often occur around 2:00 p.m. to 4:00 pm. A typical peaking power plant ramps its load up and down quickly and may stay running for two to three hours. Peaking power plants include hydroelectric and gas turbine power plants. The correlation between PV system output and electricity peak load demand make it another good choice of peaking load power plants.

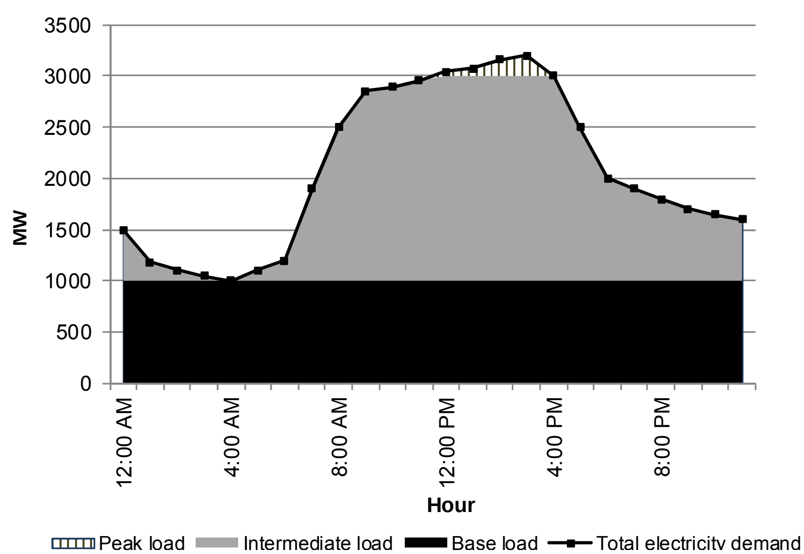


Figure 107. Electricity demand load curve of a typical day.

When the load requirement in one area varies, it is more efficient to connect many areas together via the electric grid, which is also connected to many types of power plants. Larger service areas refine load pattern and various kinds of power plants can serve base load, intermediate load, and peak load. The electric grid also allows power plants to be near their source of power, such as water, wind, or solar.

3.3.1 Interconnection and net metering.

There is growing use of distributed small scale power generation systems in recent years. Distributed energy generation is not new; however, it was suppressed by the low cost and maintenance free characteristics of large scale centralized power plants with distribution grid systems. Traditional electricity is generated in large-scale power plants and distributed in one direction through transmission lines and distribution systems to potential consumers (Figure 108).

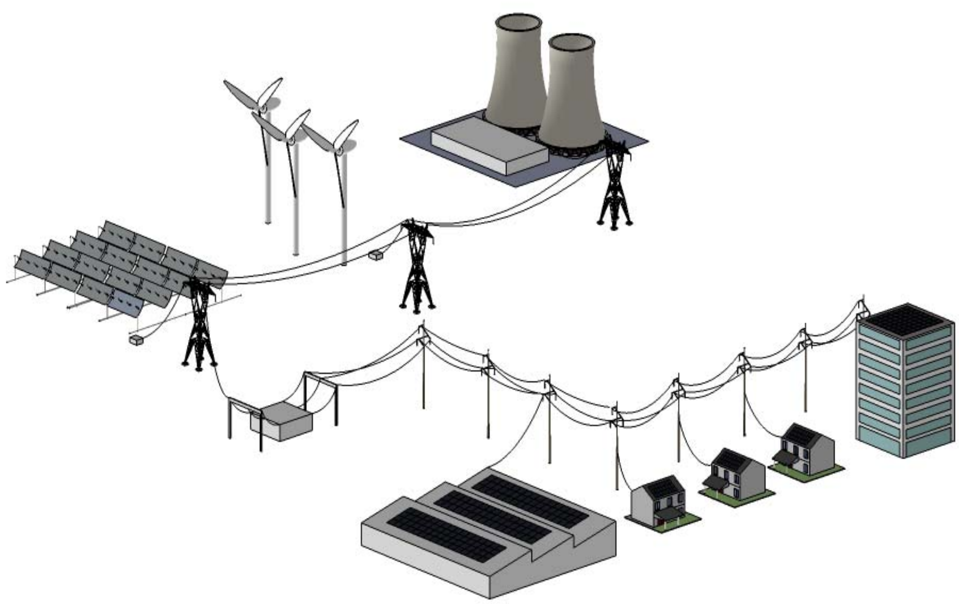


Figure 108. Conceptual diagram of power generators in electric grid systems.

Each state regulates the process of how distributed energy generators are connected to the electric distribution grid, commonly known as interconnection processes to maintain the stability and safety of the electric grid. Interconnection processes could be a barrier to the growth of distributed renewable energy generation, because the process in some areas requires too much time and money to connect PV systems to the electric grid. Normally, for systems not exceeding 2 MW, this procedure is fast and simple.

There are many benefits associated with the interconnections. Grid reliability and reserves can be improved by sharing within an interconnected network. A utility can reduce its investment in generating electricity to meet demand, and load factor is improved. This is due to peak load reduction resulting in a more steady load over time and the reduction of peak load power plants that are idle most of the time. Generation diversity mix is improved leading to supply security. Interconnection allows the dispatch of the least costly generating units within the interconnected area, providing an overall cost savings that can be divided among the component systems. Alternatively, it allows inexpensive power from one system to be sold to systems with more expensive power.

Normally, electric utility companies maintain that the aggregate of all distributed renewable energy generation capable of exporting energy on a line section will not exceed 15% of the line section’s annual peak load as most recently measured at the substation or calculated for the line. The intent of this screen is to assure that generation on a line section will not exceed load at any time, but electric utility companies typically track peak loads and not minimum loads. Fifteen percent of peak load was established in the FERC procedures as a conservative estimate of minimum load. Currently, states that allow interconnection and their capacity are shown in Figure 109. A modern inverter is used as an ideal platform for system protections, both for customers and the utility grid. It can stop current flow quickly when risky events caused by excessive volts, amps, or phase sequence are detected. It can also detect islanding situations when power outages occur at the utility grid side and stop current at the customer side from flowing back to the electric grid, which might harm workers who are fixing the problems.

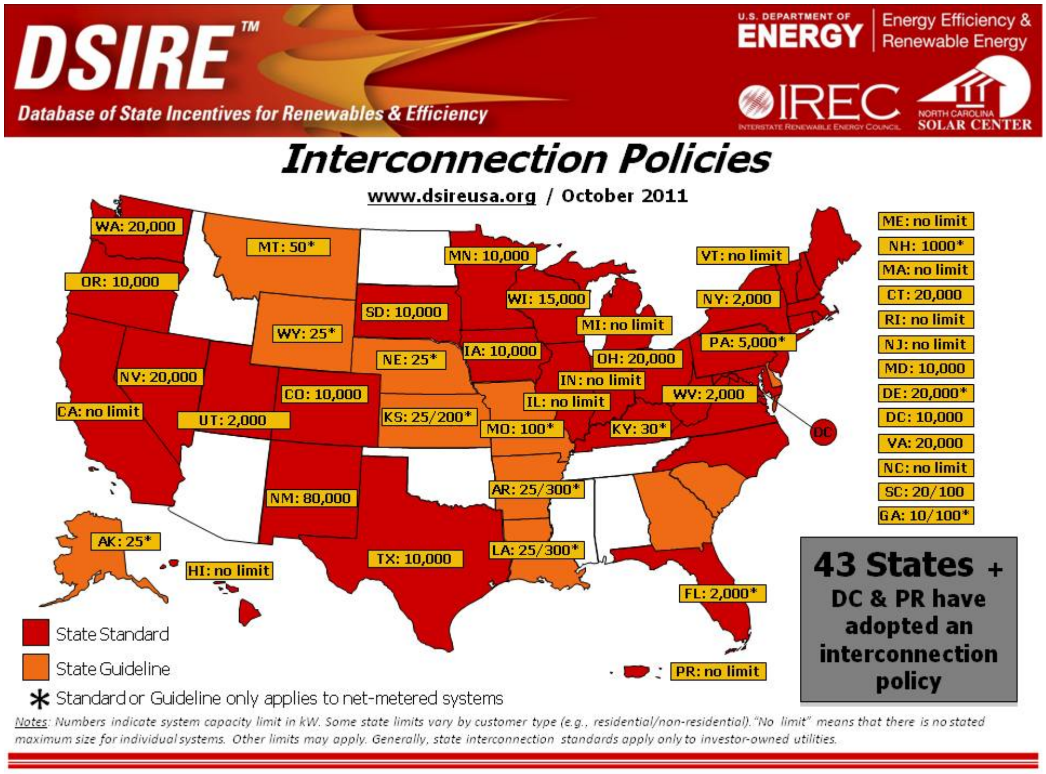


Figure 109. Interconnection policies by states (DSIRE, 2012).

For assisting the interconnection process, the Institute of Electrical and Electronics Engineers (IEEE) developed a number of consensus national standards for interconnection of distributed generators with the electric grid industry as follows:

- IEEE 1547.1 Standard for Conformance Test Procedures for Equipment Interconnecting Distributed Resources With Electric Power Systems (Approved 2005);
- IEEE 1547.2 Application Guide for IEEE 1547 Standard for Interconnecting Distributed Resources With Electric Power Systems (Approved 2008); and

- IEEE 1547.3 Guides For Monitoring, Information Exchange, and Control of Distributed Resources Interconnected with Electric Power Systems (Approved 2007).

Net metering is the policy that allows electric meters to run backwards when the electricity generated from on-site generators exceeds building demand, allowing building owners to sell this excess electricity back to the electric grid. The rates of buying vary. Some electricity utility companies buy back at retail price; some buy back at a discounted price. If electricity can be sold back at the higher rate price, it will be called a feed-in tariff, increasing the value of the electricity produced by distributed generation. Electric utility companies also benefit from net metering when customers produce their own electricity during peak periods; the system load factor is improved. Currently, net metering is offered in 43 states as shown in Figure 110.

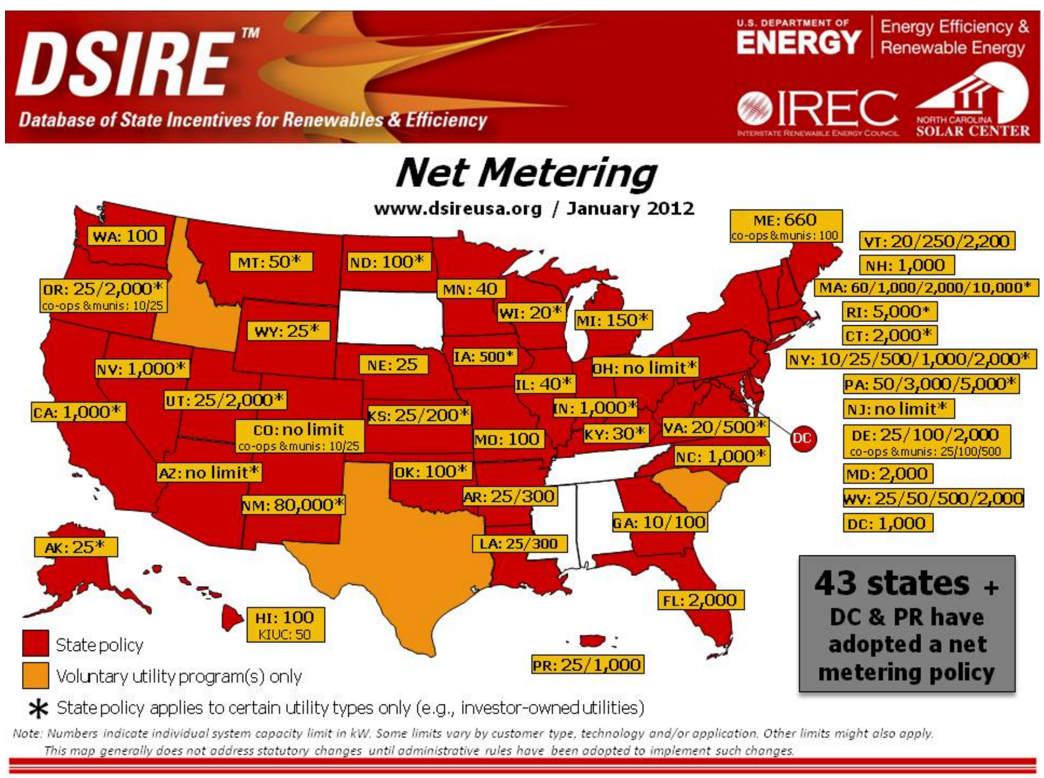


Figure 110. Net metering policies by states (DSIRE, 2012).

3.3.2 Smart grid.

An electric grid is a network of technologies that delivers electricity from power plants to consumers in their homes and office buildings. The smart grid is an automated electric power system that allows the two-way flow of electricity and information between power substations and consumers and all points in between. It can monitor and control grid activities in real time. The ability to sense, control (automatically or remotely) and monitor the system is what makes the electric grid smarter than conventional one-way control. A conceptual diagram of smart grids is shown in Figure 111.

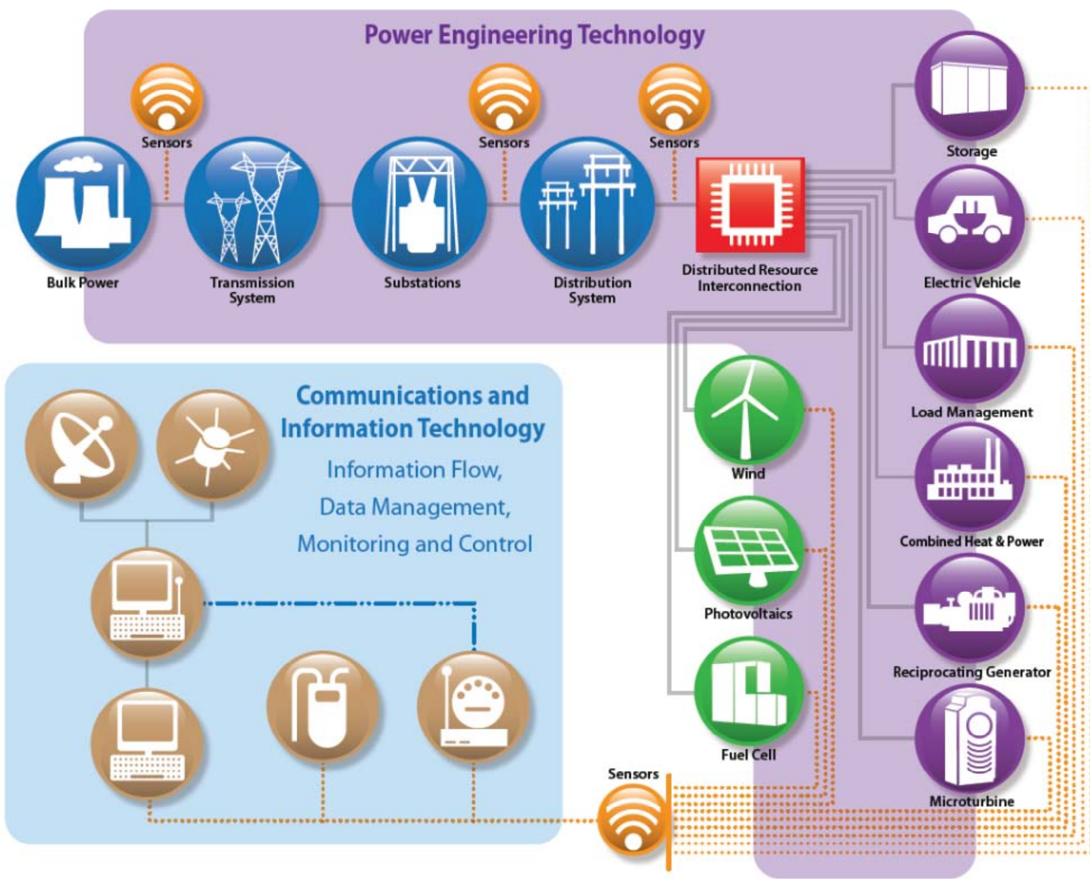


Figure 111. Conceptual diagram of smart grids (NREL, 2011a).

The electric grid is now transforming. There are growing numbers of distributed energy generators, which are often intermittent, increasing numbers of plug-in hybrid electric vehicles (PHEV or PHV), and emerging micro-grid systems. Now electric utility companies have realized the power of two-way communication through smart grid systems that can lead to a more efficient and reliable grid in utilizing electricity. National deployment of smart meters is expected to be at 48% in 2015 (Enterprise Florida & Greentech Media Inc., 2011). A smarter grid will enable many benefits, including improved response to power demand, more intelligent management of outages, better integration of renewable forms of energy, which will result in reliable and affordable electricity.

3.3.3 Policy and incentive programs.

In the United States, there are several incentive programs to promote the use of renewable energy. DSIRE, available at http://www.dsireusa.org/, is a comprehensive source of information on these incentive programs. The PV market is accelerated at a national level because of a federal tax credit equal to 30% of the investment cost (without a maximum amount) until the end of 2016. Some states have also adopted a renewable portfolio standard (RPS) regulation that sets targets for increasing production of energy from renewable energy sources such as solar, wind, geothermal, and biogas as a requirement for electric utility companies. Distributed renewable generators can also sell their certified solar electricity back to the electric utility companies. The RPS mechanism also helps accelerate PV market growth because electric utility companies create many types of rebate and incentive programs to support the installation of these solar electricity systems. More than half of the states in the United States now have renewable portfolio standards or renewable mandates (Figure 112).

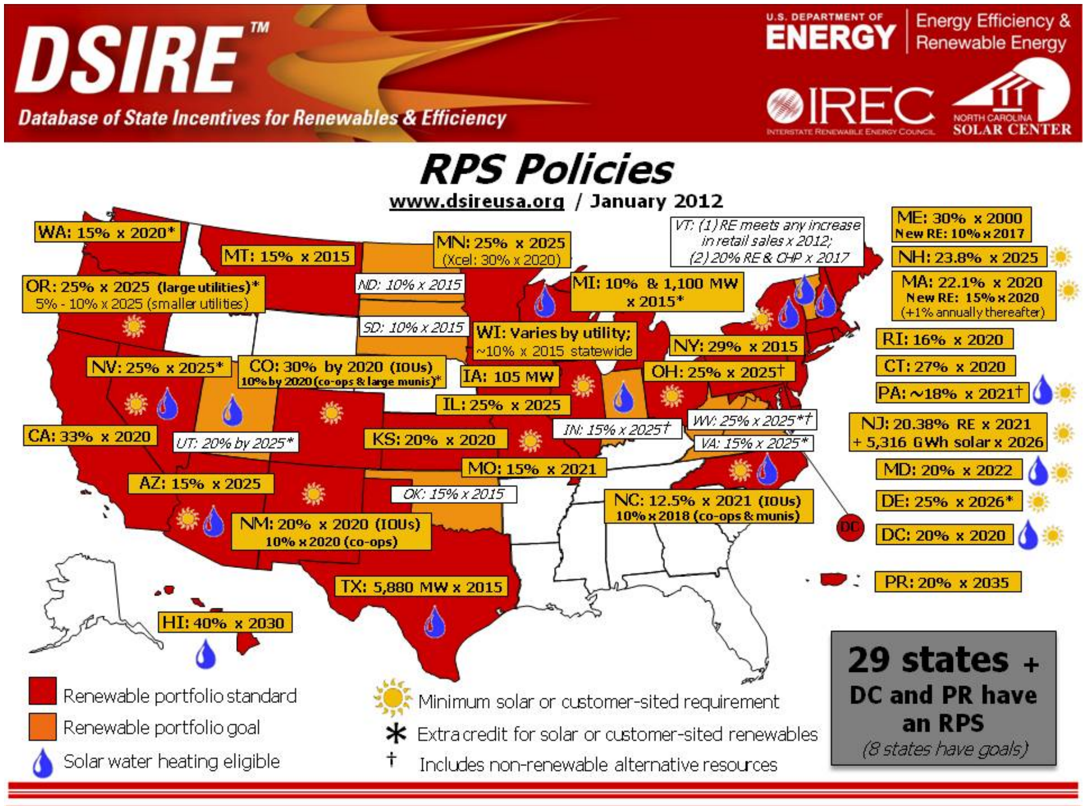


Figure 112. RPS Policies by states (DSIRE, 2012).

3.3.4 Impact to the electric grid.

a) Case studies.

Two case studies located in Ann Arbor, Michigan were examined for their potential when grid-connected PV systems were implemented with a group of buildings. They are Fleming Creek Resident and North Campus Research Complex (NCRC). In Fleming Creek Resident, 4 kW DC PV systems were applied on the roof of every house. In NCRC, energy efficiency design strategies and PV system full roof size were applied. The weather data used in the NCRC study was from SolarAnywhere®, which is actual location-time specific weather data. For Ann Arbor, the availability of actual PV system outputs can vary from -28% to +17% compared with traditional use of TMY3 weather data set. If the time is permitted, detail simulation using SolarAnywhere® multi-year data sets can capture variation and uncertainty of PV system outputs, which is essential for PV system design and operation. With this knowledge, suitable management and operation options can be determined. Detailed information about the impact of using different weather data sets in Ann Arbor, Michigan can be found in ”Impact of different weather data sets on photovoltaic system performance evaluation” (Yimprayoon & Navvab, 2011b).

The Fleming Creek Resident, located in the northeastern part of Ann Arbor, Michigan (Figure 113), is in climate zone 5A, which is classified as humid continental (warm summer). Its latitude and longitude are 42.22N and 83.75W. Sun shines on the southern face of the house all year round.

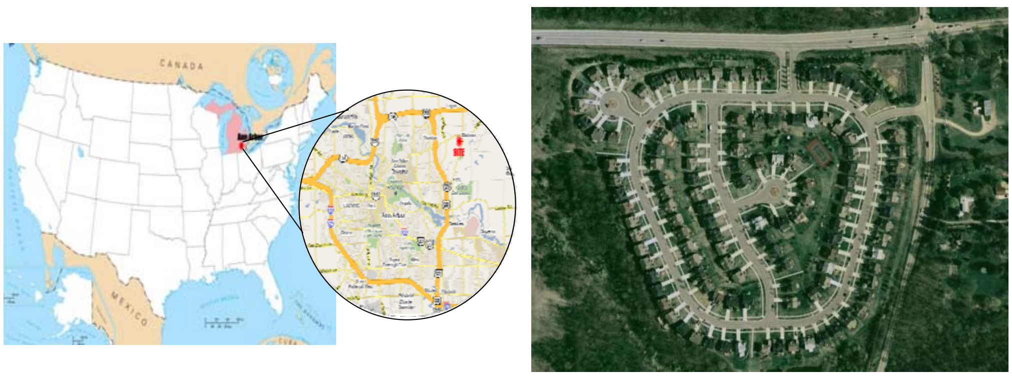


Figure 113. Fleming Creek resident location and site plan.

Fleming Creek is a residential complex constructed in the 1990s. There are 122 medium-sized detached houses. The house sizes range from 160 m^2-280 m^2 with roof areas ranging between 180 m^2-240 m^2. In this particular example, the front of the house orientation shared by the greatest number of houses is northeast, followed by northwest. The solar radiation falling on roofs facing in each direction around the compass at a tilt angle of 30° from horizontal as well as the total output AC energy were computed using PVWATTS1.0. The TMY2 data of Detroit was used instead of Ann Arbor because it is the closest place that is available in the program. It is assumed that every house is able to find areas on its back roof to accommodate a PV system at 4 kW DC. The systems can produce electricity at 2,850-4,565 kWh/year, depending on orientations of the systems. The total electricity output is as high as 458

MWh/year or, on average, 3.75 MWh/house. This total PV electricity output equaled 0.87% of the estimated 2010 annual electricity consumption that Detroit Edison, the electric utility company in this area, needed to supply. More information about this study can be found in “Residential Housing Photovoltaic System Performance in a Northern Climate” (Yimprayoon & Navvab, 2010).

North Campus Research Complex (NCRC) is the former Pfizer pharmaceutical research facility. The University of Michigan bought this facility in 2009 to instantly expand its research capabilities (North Campus Research Complex, 2010). The facilities include 4 parcels totaling 173.5 acres of land area, 28 buildings with 39,033 m^2 (420,000 ft^2) of administrative space, and 111,524 m^2 (1.2 M ft^2) of research space, interior furnishings, manufacturing and technical equipment, and 2,800 parking spaces (Figure 114).

Figure 114. North Campus Research Complex (NCRC).

More than 50% of energy use in the existing condition was due to electricity demand. If grid-connected PV systems are installed on 60% of the rooftop area, the system size would be 5.2 MW. The output would account for 13% of the actual total electrical loads. If the NCRC is renovated to meet the ASHRAE 90.1 energy standard, the electricity used would be only 23% of the existing condition, making it easier for PV system output to meet the electricity load demand. The electric grid-connected PV systems can also help lower peak load demand by 9% (Figure 115 and Figure 116). However, without an economic incentive, the payback period is very long. Local governments and electric utility companies can use results from this study to plan their incentive programs and net metering requirements. More information about this study can be found in "Applications of Grid-Connected Photovoltaic System in Large Institutional Buildings" (Yimprayoon & Navvab, 2011a).

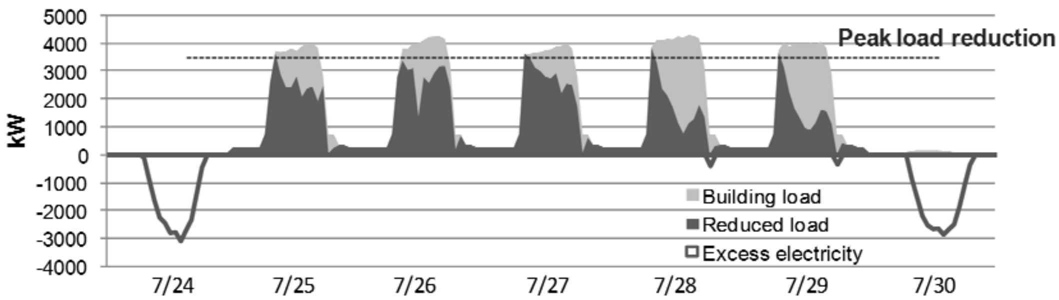


Figure 115. NCRC load profile compared with PV electricity output in summer (July).

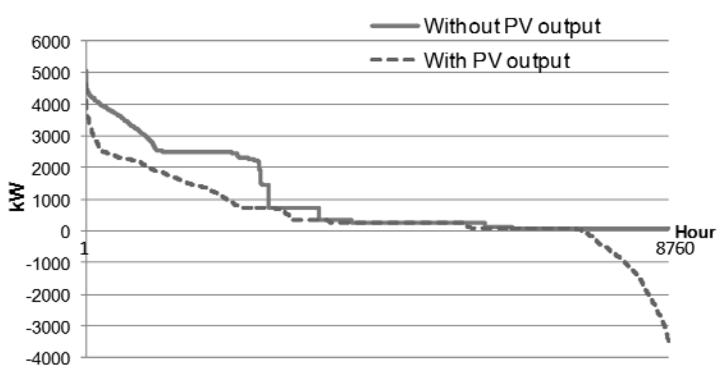


Figure 116. Load duration curve with and without PV electricity output.

b) Use patterns for groups of buildings and electricity output patterns in different climates.

Given its intermittency characteristic, electricity output from PV systems is harder to manage compared with traditional fossil fuel power plants. More understanding of its behavior and real time monitoring can lead to efficient management of this type of energy source. In this section, electricity use patterns from groups of buildings and PV electricity output patterns in different climate zones are examined. Miami, Baltimore, and Duluth – which represent hot, cool and cold weather – are presented here. The proportions of residential buildings to commercial buildings to industrial buildings in a group of buildings were taken from electric utility companies' customer numbers in studied cities. Electric utility companies' load and customer information database can be found at FERC Form No. 714 Annual Electric Balancing Authority Area and Planning Area Report (Federal Energy Regulatory Commission, 2011) and the Utility Rate Database (URDB). This data is voluntarily submitted by electric utility companies.

The numbers of residential, commercial, and industrial customers of Florida Power and Light Company (Miami) in 2010 were 3,985,549, 506,630, and 10,780, respectively, which is equal to approximately 4,000:500:10. 2010 forecasted summer peak was 21,922 MW and 2010 forecasted winter peak was 24,346 MW. 2010 forecasted annual demand was 109,886 MWh. Because of the lack of data for Duluth, the Minnesota Municipal Power Agency's data, which serves nearby areas, was used. The numbers of residential, commercial, and industrial customers are 121,217, 22,167, and 429, respectively which is equal to approximately 2,800:500:10. 2010 forecasted summer peak was 1,200 MW, and 2010 forecasted winter peak was 1,414 MW. 2010 forecasted annual demand was 7,509 MWh. For comparison, the proportion of residential:commercial: industrial buildings equal to 4,000:500:10 was used in all cities.

Within each building type, proportions of the building size were taken from EIA national energy consumption survey, RECS, CBECS, and MTECS. Small houses accounted for 70% and medium houses accounted for 30%. For commercial buildings, small office buildings accounted for 73%, medium office building accounted for 25%, and big office buildings accounted for 2%. Figure 117 - Figure 119 show the potential of energy efficiency design strategies and PV systems in reducing annual electricity consumption and peak electricity demand from a group of buildings in Miami, Baltimore, and Duluth. These results are from the aggregation of electricity demand and electricity outputs of 2,800 small houses, 1,200 medium houses, 365 small office buildings, 125 medium office buildings, 10 big office buildings, and 10 factory buildings. Building electricity demand and typical PV size electricity output were calculated in five conditions: 1) existing, 2) ASHRAE compliant, 3) all buildings are applied with the most annual electricity-reducing strategies, 4) all buildings are applied with the most peak electricity-reducing strategies, and 5) all buildings are applied with ZEB strategy. These results are shown with and without PV typical size output to demonstrate the effect of electricity from PV systems. Percentage comparisons to existing buildings without PV electricity are also shown.

Commercial buildings are the electricity consumer group that has high impact on overall electricity patterns and demands. The industrial building group has the lowest impact. Overall, compliance with ASHRAE standards can reduce electricity consumption 23% in Miami, 15% in Baltimore, and 16% in Duluth. With PV systems, an additional reduction of 14% to 18% can be expected. Using ZEB strategy with PV systems can reduce annual electricity consumption 46% to 51%. For peak electricity reduction, compliance with ASHRAE standards can reduce peak electricity demand 20% in Miami, 22% in Baltimore, and 17% in Duluth. If buildings are installed with typical PV size systems, peak electricity demand can be reduced further by 2% in Miami, 4%-5% in Baltimore, and 7%-10 % in Duluth. When PV systems are installed in conjunction with building-implemented energy efficiency design strategies, the total peak electricity reduction is less than the sum of peak electricity reductions. Using ZEB strategy with PV systems can reduce peak electricity demand 39% to 48%. With PV electricity output, peak electricity demand periods were also changed, especially in summer, from late afternoon to early morning. In winter, the peak electricity demand period remained at the end of the day. Excess electricity occurs during holidays and winter working days when the sun is strong. It can be used to reduce electricity supply to buildings without PV systems. At the higher rate of PV system penetration into the electric grid, the need for energy storage increases in order to prevent electricity dumping to maintain the electric grid system balances.

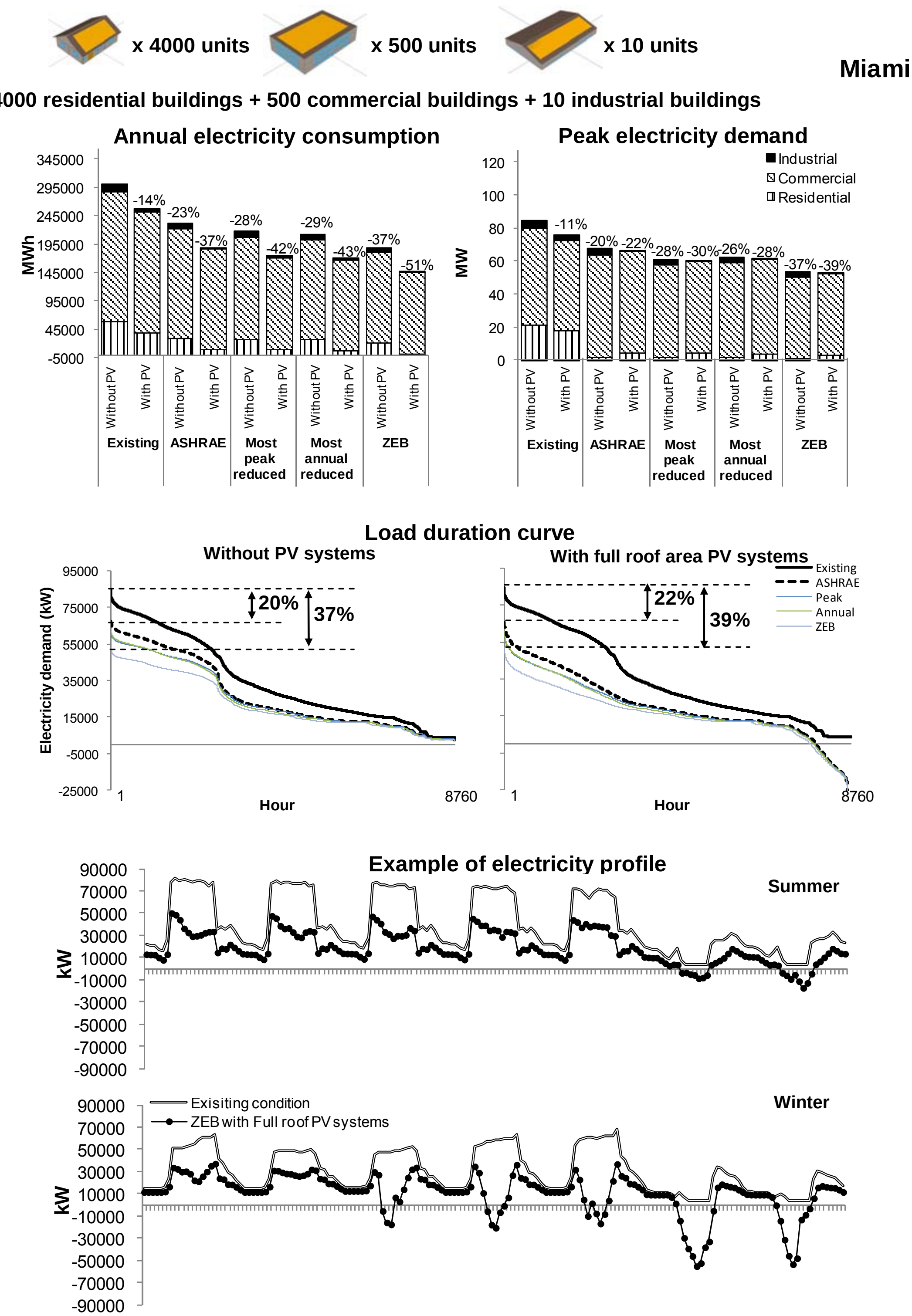


Figure 117. Potential of energy efficiency design strategies and PV systems to reduce annual electricity consumption and peak electricity demand when applied to a group of buildings in Miami.

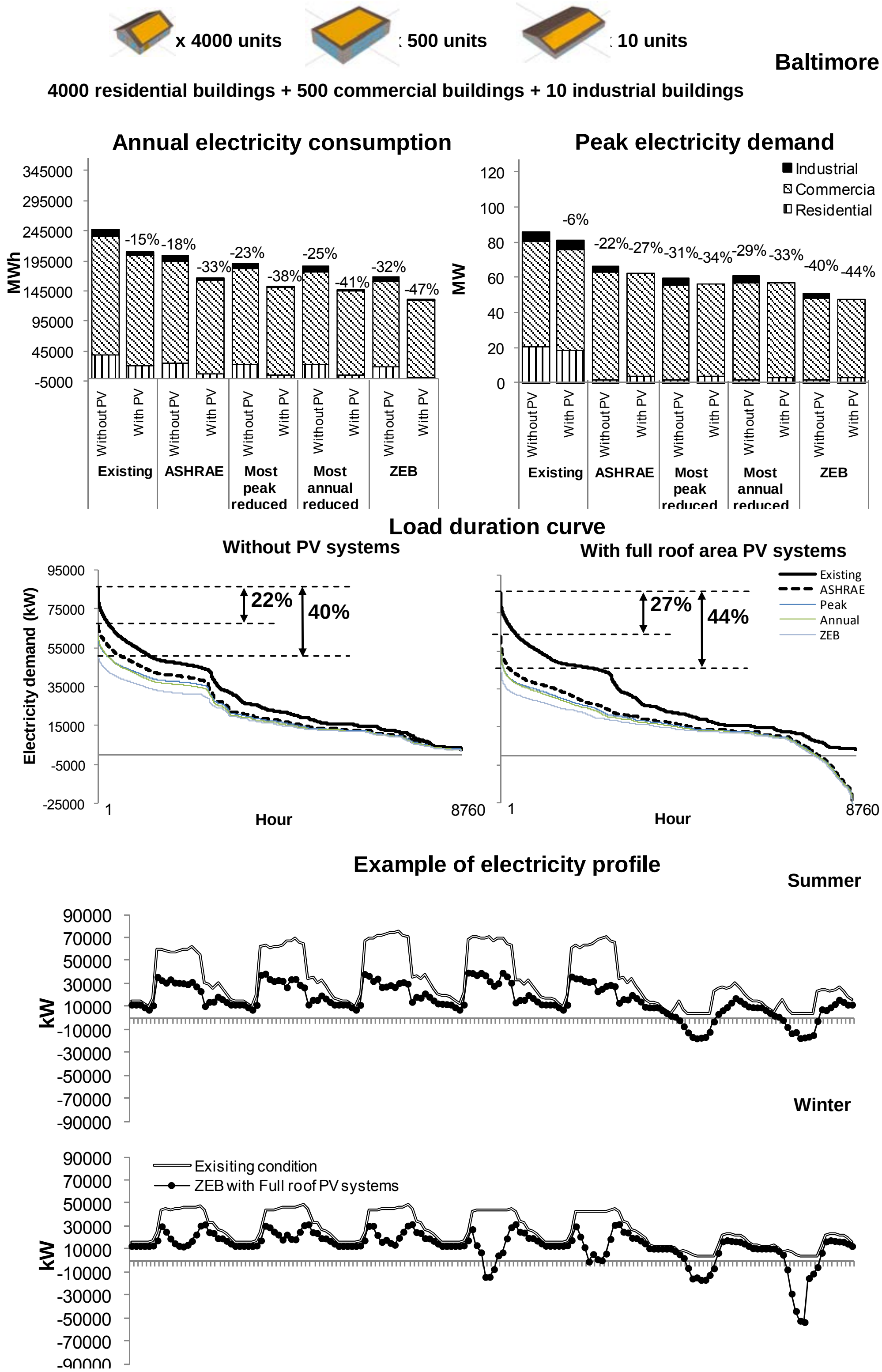


Figure 118. Potential of energy efficiency design strategies and PV systems to reduce annual electricity consumption and peak electricity demand when applied to a group of buildings in Baltimore.

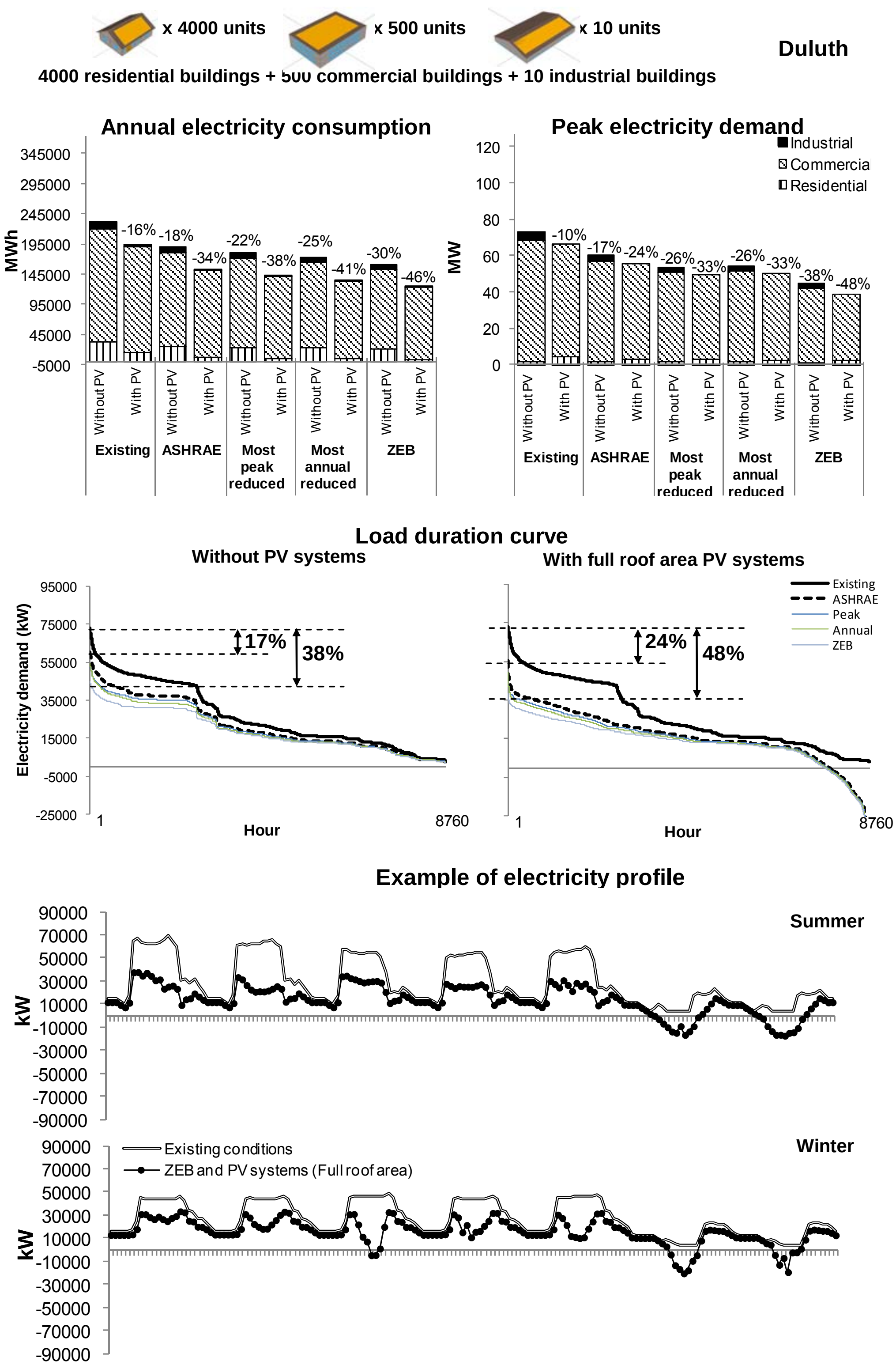


Figure 119. Potential of energy efficiency design strategies and PV systems to reduce annual electricity consumption and peak electricity demand when applied to a group of buildings in Duluth.

From available databases used in this study, predictions can be made concerning the savings for the various energy efficiency design strategies as well as PV electricity output in any combination of building numbers. Given the dynamic of real building pattern of use and daily weather, there exists uncertainty in energy use and PV production. However, these uncertainties can be estimated by applying different situations and obtaining the possibility of plus or minus load data and PV electricity output.

3.4 Conclusions

In this chapter, basic information concerning grid-connected PV systems and solar energy resources was presented. PV system technologies and solar resources in the form of weather data were selected as inputs in computer simulations using SAM software. Simulation methodologies were described. PV systems areas were based on roof areas available on basecase building models described in chapter 2, section 2.4.2. Five PV technologies, c-Si, HIT, CdTe thin film, Triple Junction a-Si, and future high performance PV were selected for initial PV electricity output modeling. Then PV electricity output from c-Si technology was selected for further analysis because it represented the highest PV electricity output performance using today's technology. Grid-connected PV system performances were then analyzed together with energy efficiency design strategies implementation. Annual electricity consumption reduction, peak electricity demand reduction, and excess electricity reduction as well as impacts to the electric grids, were examined. Energy efficiency design strategies were also prioritized according to their ability to reduce annual electricity consumption, reduce peak electricity demand, and increase building electricity load met when implemented with PV systems.

3.4.1 Annual electricity consumption reduction.

With grid-connected PV systems, the annual electricity consumption reduction can be determined by subtracting annual electricity consumption after energy efficiency design strategies were applied with PV electricity annual output.

- **Residential building:** Reducing lighting power density was the most effective single strategy in reducing annual electricity consumption, followed by using high efficiency appliances in residential buildings. The proportion of electricity savings is higher in residential buildings with 24-hour use schedule. Small houses can achieve zero electricity consumption with the ZEB strategy and PV 4 kW size systems.
- **Commercial buildings:**
    - Small office buildings: The best single strategy is daylighting, followed by reduced lighting power density.
    - Medium office buildings: Using high efficiency appliances was the most effective single strategy. Reducing lighting power density was the second best single strategy in hot and mild climates while daylighting was second in cold climates. ZEB strategy can reduce electricity use approximately 30% compared with existing buildings. PV typical size at 30 kW DC accounted for 4%-5% annual existing building electricity consumption. Full-roof PV size at 225 kW DC can satisfy 29%-36% annual existing building electricity consumption.
    - Big office buildings: Using high efficiency appliances was the most effective single strategy. Reducing lighting power density was the second best single strategy in all climates.
    - The effect of increasing building use schedule on electricity savings from energy efficiency design strategies was low in commercial buildings.
- **Industrial buildings:** Reducing lighting power density was the most effective single strategy, followed by increasing cooling system efficiency in hot climates and using high efficiency appliances in mild and cold climates. The effect of increasing building use schedule to

electricity saving from energy efficiency design strategies was low in industrial buildings.

3.4.2 Peak electricity demand reduction.

For peak electricity reduction, building electricity demand in each hour was subtracted by PV hourly output. Then the highest demands in the whole year were identified as peak demands. Sometimes, peak electricity demand periods were also changed from doting the day to the early morning or at the end of the day because PV output can reduce peak demand during the day.

Generally, the duration of the days is longer in summer resulting in longer duration of PV electricity output from available solar radiation which can help reducing parts of electricity demand that occur during 5-7 pm. Daily electricity demand and PV electricity output from PV systems are also higher in summer. Therefore, PV systems can be of more benefit in summer to reduce peak electricity demand than in winter when the duration of sunlight reaching the earth during the day is shorter and the heating demand which mostly need natural gas as energy source is dominant. Excess electricity is also higher in winter.

- **Residential buildings:** The greatest reduction in peak electricity demands in residential buildings was achieved using energy efficiency design strategies. PV electricity output had a small effect because it occurs during daytime when people are at work. Increasing building envelope insulations and glazing performance was the most effective single strategy in reducing peak electricity consumption in hot climates. In mild and cold climates, the best strategies were increasing cooling system efficiency and reducing lighting power density.
- **Commercial buildings:** In small and medium office buildings, increasing cooling system efficiency was the best single strategy in hot and mild climates. In mild and cold climates, daylighting was the best single strategy for reducing electricity demand. In big office buildings, using

high efficiency appliances was the best single strategy, followed by reducing lighting power density in all kinds of climates.

- **Industrial buildings:** increasing cooling system efficiency was the best single strategy, followed by reducing lighting power density. The peak electricity demand reduction percentage numbers increased with colder weather and with the proportion of PV system size to building electricity loads. However, higher proportion of PV system size to building electricity loads also resulted in more excess electricity to the electric grid.

Buildings with 24-hour use schedules can have a positive impact on peak electricity demand reduction percentages by applying energy efficiency design strategies and installing PV systems, if they are residential buildings. The impact is negative in commercial and industrial buildings. When energy efficiency design strategies and PV systems were implemented together in buildings, peak electricity demand reduction percentage numbers were less than the sum of reduction percentages when they were implemented separately. This is because they reduce peak electricity demand at different periods.

3.4.3 Building electricity load met and excess electricity reduction.

Some energy efficiency design strategies can increase PV electricity output utilization or load met better than other strategies when implemented with grid-connected PV systems. In residential buildings, reducing lighting power density is the best single strategy that can increase building electricity load met percentages. Reducing lighting power density and increasing cooling system efficiency are the best single strategies in commercial buildings. Reducing lighting power density, increasing cooling system efficiency, and thermal mass are the best single strategies in industrial buildings. Bigger size PV systems can increase load met percentages, but if it is too big, excess electricity will also increase.

3.4.4 Impact to the electric grids.

Two case studies located in Ann Arbor, Michigan were examined for their potential when PV systems were implemented on a group of buildings. The results demonstrated a high potential for grid-connected PV systems when implemented in clusters of buildings. The Fleming Creek resident with 122 medium-size houses, each with a 4 kW DC grid-connected PV system at their roof, can produce total PV electricity output equal to 0.87% of estimated 2010 annual electricity consumption, which local electricity utility companies in this area needed to supply. With available incentive programs at the time of the analysis, simple payback period for the whole community is 20 years. At another project, the NCRC which is the 28-building research facility, a 5.2 MW grid-connected PV system could be installed on the available roof area. The output would account for 13% of the project's actual total electrical load and can also help lower peak load demand by 9%. However, the local utility only allows a 20 kW or smaller PV system size for a net-metering program. Financial and policy constraints that exist in many states can prevent the implementation of this kind of project.

With available building modeling, electricity demand, and PV electricity output database, various combinations of buildings and their electricity demand after energy efficiency design strategies and PV systems are implemented can be examined. This chapter presented an example of a group of 4,510 buildings comprised of residential, commercial, and industrial buildings located in Miami, Baltimore, and Duluth with the proportion of residential to commercial to industrial building equal to 4,000:500:10. The result showed that commercial buildings are the main electricity consumer and dominate the electricity profile patterns. Compliance with ASHRAE standards can reduce annual electricity consumption 15% to 23%. With PV systems, 14% to 18% more reduction can be expected. Using ZEB strategy with PV systems can reduce annual electricity consumption 46% to 51%. For peak electricity reduction, compliance with ASHRAE standards can reduce peak electricity demand 17% to 22%. With PV systems, an additional

2% to 10% reduction can be expected. Using ZEB strategy with PV systems can reduce peak electricity demand 39% to 48%.

Results in this chapter can give guidelines for energy efficiency design strategies selection for each building type to meet different goals. Available databases of residential, commercial, and industrial buildings implementing energy efficiency design strategies and PV systems in 16 climates allow opportunities for electric utility companies to explore different options in implementing PV systems with energy efficiency buildings. Using various energy efficiency design strategies, PV electricity output in any combination of building numbers can be predicted. Other performance, such as investment and environmental impacts in the form of CO_{2e} emission, could also be considered when selecting energy efficiency design strategy options. These performances were investigated and their results are presented comparing them with other performances in chapter 4.

CHAPTER 4
ANALYSIS METRICS AND DISCUSSION

When choosing appropriate energy efficiency design strategies, many aspects can be considered. Individual projects have goals to achieve as determined by design teams or clients. These goals could range from building codes, rating systems, standards, and targets from design teams or clients. This chapter presents strategic performance metrics in the form of radar charts for easy comparison. First, each metric and its calculation methods are discussed, then the results and discussion are presented. These metrics can help design teams and project owners choose among the available energy efficiency design strategy options that suit their goals.

4.1 Analysis Metrics

Energy saving potential, financial analysis and environmental impact are the main criteria used in evaluating design options for decision making. Seven performances representting electricity use reduction, impact to electric grids, financial investment, and greenhouse gas emission were selected and presented in this study. They are as follows:

- Building annual electricity consumption reduction.
- Building peak electricity demand reduction.
- Excess PV electricity output.
- Building load power met.
- Investment cost.
- Simple payback period.
- Greenhouse gas emissions from site energy.

These goals can be prioritized to suit individual projects. Examples of their actual performance in small houses, medium office buildings, and factory buildings located in Miami, Phoenix, Las Vegas, Baltimore, Chicago and Duluth are presented in Appendix B. Details of each performance calculation are presented in sections 4.1.1, 4.1.2 and 4.1.3.

4.1.1 Reduced building electricity consumption and reduced peak electricity demand.

Reducing energy expenses is normally the main goal when considering energy efficiency design strategy options for buildings. Electricity expenses – especially in large buildings – are combinations of the amount of electricity used, how and when the peak electricity use occurs, and sometimes the quality of building equipment that affected the reactive power. Electricity consumption reduction and peak electricity demand reduction are selected as key performances that represent each energy efficiency design strategy performance when implementing them with grid-connected PV typical size systems. To calculate these performances, building simulations were performed. Building stock modeling is explained in detail in section 2.4. Grid-connected PV systems modeling is explained in detail in section 3.1.6. The potential of energy efficiency design strategies and PV systems in reducing annual electricity consumption and reduced peak electricity demand are presented in sections 3.2.1and 3.2.2.

4.1.2 Excess PV electricity output and building electricity load met.

Excess PV electricity output in the electric grids is currently at a very low rate because of the low penetration of grid-connected PV systems. The excess electricity at low penetration rate can be a benefit to the electric grid system, because it can be used to satisfy peak electricity demand. However, when the renewable energy penetration rate into the electric grid system is higher in the future, energy storages are needed and the peak reduction benefit decreases. It is generally better that PV electricity output can be used as much as possible before the excess output is sent out to the electric grids. The calculation details of excess electricity and building load power met by electricity output from PV systems can be found in section 3.2.3.

Excess electricity and building load power met by electricity output from PV systems presented in radar graphs are percentage numbers of excess electricity and percentage number of percentage load met by PV electricity output compared with buildings implementing the ZEB strategy and grid-connected PV typical size systems.

4.1.3 Economic analysis.

Economic analysis is the main drive in any energy efficiency investment. Investment cost and simple payback period are two performance metrics presented. Details of each parameter used in the economic analysis are outlined as follows.

a) Energy price.

Electricity average retail prices for 2011 year-to-date are available from the EIA at http://www.eia.gov/electricity/monthly/excel/epmxlfile5_6_b.xls. Natural gas prices are also available from the EIA at http://www.eia.gov/dnav/ng/ng_pri_sum_dcu_nus_m.htm. In this study, the data in the analysis sections are shown with electricity expense using national electricity and natural gas price averages as indicated in Figure 120.

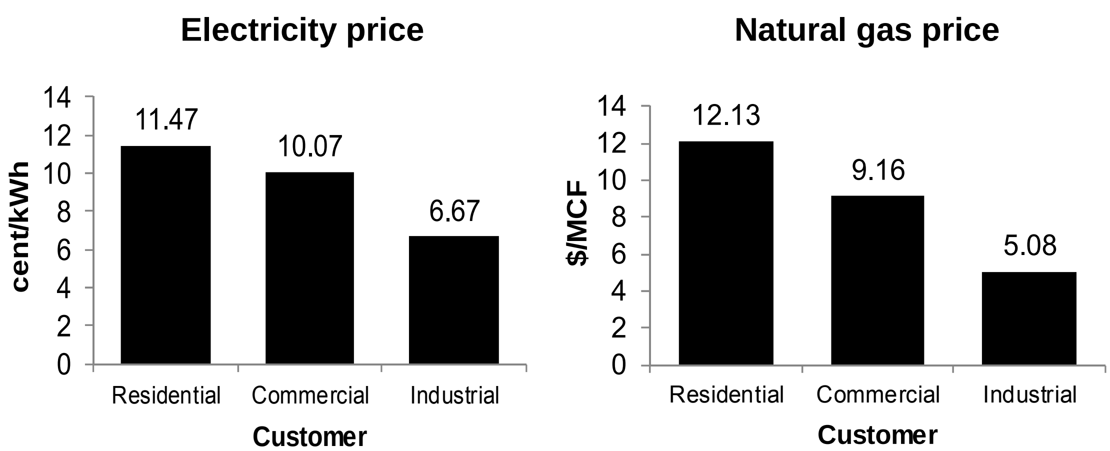
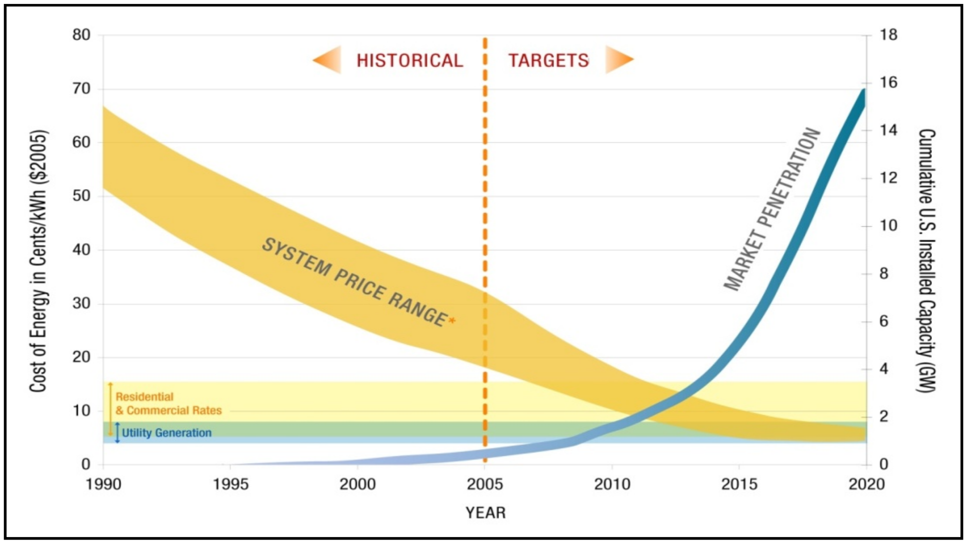


Figure 120. Average electricity and natural gas prices by customer sectors used in this study as of May 2011.

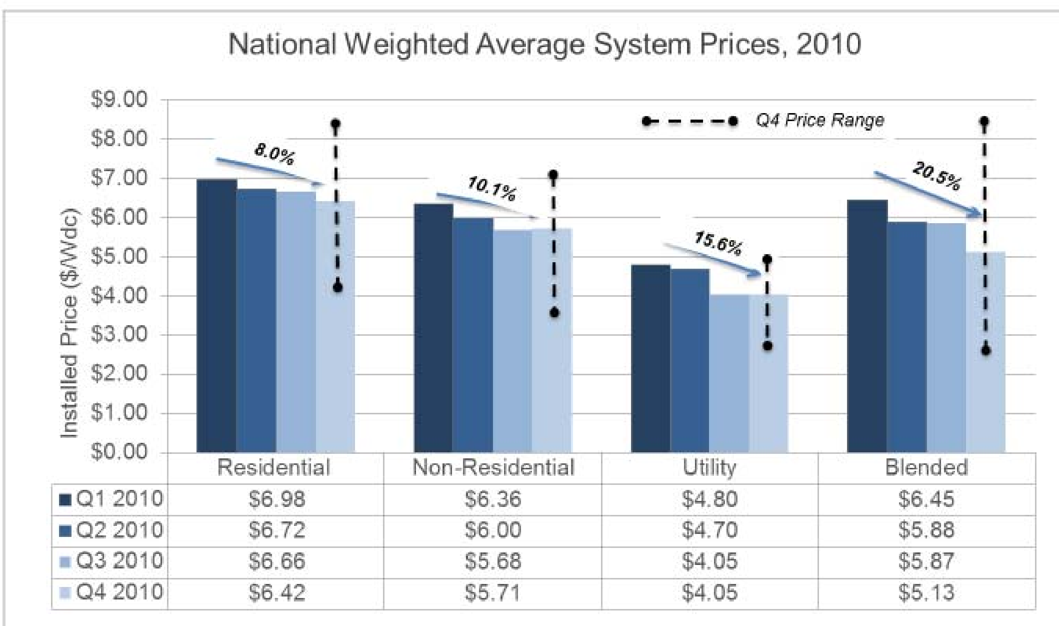
b) PV system cost.

Photovoltaic cost is likely to continue to decrease in the future. Technological improvements, such as producing higher efficiency modules, increased reliability, improved manufacturing processes, and improved accessories efficiency and cost, are being developed. Figure 121 shows average cost per kWh and predicts that it is likely to decrease in the future. Today, the price of PV systems is between \$3-\$18/watt installed, depending on the system, the existing structure, and available incentives. The average \$9/watt installed system is used primarily for feasibility calculation. The goal of improving PV systems is to drive cost below \$3/watt installed (or \$0.15/ kWh) in order to compete with conventional electrical rates, which are about \$0.11/kWh. A recent market analysis done by GMT indicated that PV system prices are steadily decreasing (Figure 122).



Market Sector	Current U.S. Market Price Range (¢/kWh)	Cost (¢/kWh) Benchmark 2005	Cost (¢/kWh) Target 2010	Cost (¢/kWh) Target 2015
Residential	5.8-16.7	23-32	13-18	8-10
Commercial	5.4-15.0	16-22	9-12	6-8
Utility	4.0-7.6	13-22	10-15	5-7

Figure 121. Photovoltaic system cost history (NREL, 2011a).



Source: GTM Research/SEIA® *U.S. Solar Market Insight™: 2010 Year-in-Review*

Figure 122. 2010 PV system cost per kW DC (GTM Research, 2011).

In this study, $8/W DC installed was used for residential PV system investments while $7/W DC installed was used for commercial and industrial system investments. The PV system investment costs are shown in Table 32.

Table 32. PV systems investment cost.

Building type	PV typical size (kW DC)	Cost ($)/ W DC installed	Investment cost ($)
Small/medium houses	4	8	32,000
Small office buildings	20	7	140,000
Medium office buildings	30	7	210,000
Big office buildings	100	7	700,000
Factory buildings	500	7	3,500,000

Assuming that a PV system lifetime is 30 years, the costs of electricity from PV per kWh for each building type in 6 cities are shown in Table 33. Larger systems, more available solar radiation, and proper tilt angles of the system are the main factors that can bring the PV electricity cost per kWh down in this example.

Table 33. PV electricity cost per kWh.

Cities	Small houses ($/kWh)	Medium houses ($/kWh)	Small office buildings ($/kWh)	Medium office buildings ($/kWh)	Big office buildings ($/kWh)	Factory buildings ($/kWh)
Miami	0.22	0.22	0.17	0.19	0.18	0.16
Phoenix	0.18	0.18	0.14	0.16	0.16	0.14
Las Vegas	0.18	0.18	0.19	0.16	0.16	0.14
Baltimore	0.24	0.24	0.19	0.22	0.21	0.18
Chicago	0.25	0.25	0.20	0.23	0.22	0.19
Duluth	0.24	0.24	0.20	0.23	0.22	0.19

c) Energy efficiency design strategies investment cost.

The increment cost of energy efficiency design strategies is based on the differences between the cost for the strategies and the cost of options used in ASHRAE 90.1-2007 and ASHRAE 90.2-2007 compliant-models. Energy efficiency investment costs and lifetime data were primarily obtained from the DOE's energy efficiency measures and costs website at http://www1.eere.energy.gov/buildings/building_america/measures_costs.html. Other sources of investment cost were RS means building cost 2009 (R. S. Means, 2009), EIA Technology Forecast Updates-Residential and Commercial Building Technologies Report (Navigant Consulting Inc., 2007), and distributors' websites. The summary of investment cost estimating methods is listed in Cost related to retrofitting existing buildings to meet the ASHRAE standard is not presented here. This is because the U.S. DOE Building Energy Code Program (BECP) has been studying the impact of ASHRAE standards on buildings in the U.S., which includes investigating the percentage of energy reduction and energy expense reduction in different climate zones and with different code implementation in selected states. More information can be obtained from its website at http://www.energycodes.gov. Groups of energy efficiency design strategies are also explored by many research teams in order to support the Advance Energy Design Guides (AEDG), which can reduce energy use in selected commercial buildings beyond 50% compared with ASHRAE90.1-2004. Technical support document for AEDG is available from NREL website.

Table 34. The cost of some measures, such as adding wall insulation and increase cooling and heating system efficiency, vary from climate to climate and project to project. This is because the level of insulation added varies among climates and there are different requirements between residential and commercial buildings. The sizes of cooling and heating systems also vary among building types and climates.

Cost related to retrofitting existing buildings to meet the ASHRAE standard is not presented here. This is because the U.S. DOE Building Energy Code Program (BECP) has been studying the impact of ASHRAE standards on buildings in the U.S., which includes investigating the percentage of energy reduction and energy expense reduction in different climate zones and with different code implementation in selected states. More information can be obtained from its website at http://www.energycodes.gov. Groups of energy efficiency design strategies are also explored by many research teams in order to

support the Advance Energy Design Guides (AEDG), which can reduce energy use in selected commercial buildings beyond 50% compared with ASHRAE90.1-2004. Technical support document for AEDG is available from NREL website.

Table 34. Cost calculation method summary.

Measures	Methods	References
Super-insulation: Wall	Exterior wall area times incremental cost of higher insulation value.	(R. S. Means, 2009),(NREL, 2012b)
Super-insulation: Roof	Ceiling areas times incremental cost of higher insulation value.	(NREL, 2012b)
High-performance windows	Window area times incremental cost of higher performance windows.	(NREL, 2012b)
Thermal mass	Increment cost of mass interior wall and mass floor compared with lightweight interior wall and ASHRAE-compliant floors.	(R. S. Means, 2009)
Daylighting	Incremental cost of dimmable light bulbs and control systems.	(NREL, 2012b)Distributor website
Cooling system efficiency	System peak demand multiplied by 1.15 and then multiplied by increment cost of higher efficiency units.	(NREL, 2012b; Navigant Consulting Inc., 2007)
Heating system efficiency	System peak demand multiplied by 1.25 and then multiplied by increment cost of higher efficiency units.	(NREL, 2012b; Navigant Consulting Inc., 2007)
Lighting power density	Incremental cost of higher efficiency light bulbs.	(NREL, 2012b)
High efficiency appliances	Incremental cost of higher efficiency appliances.	(NREL, 2012b)
Thermostat setting	No cost	(NREL, 2012b)
Cooling desk temperature reset	No cost	(NREL, 2012b)
Passive house	Combined cost of improved air tightness, solar water heater, super insulations, high performance window, reduced LPD and higher efficiency appliances.	(R. S. Means, 2009), (NREL, 2012b)
ZEB	Combined cost of solar water heater, super insulations, high performance window, reduced LPD, higher efficiency appliances and higher efficiency HVAC systems.	All sources

Table 35 - Table 37 show investment costs of each energy efficiency design strategy for small houses, medium office buildings, and factory buildings calculated using methods mentioned in Cost related to retrofitting existing buildings to meet the ASHRAE standard is not presented here. This is because the U.S. DOE Building Energy Code Program (BECP) has been studying the impact of ASHRAE standards on buildings in the U.S., which includes investigating the percentage of energy reduction and energy expense reduction in different climate zones and with different code implementation in selected states. More information can be obtained from its website at http://www.energycodes.gov. Groups of energy efficiency design strategies are also explored by many research teams in order to support the Advance Energy Design Guides (AEDG), which can reduce energy use in selected commercial buildings beyond 50% compared with ASHRAE90.1-2004. Technical support document for AEDG is available from NREL website.

Table 34. In this study, the reduction of HVAC system size because of reduced load from improving building envelope or reduced lighting and appliance load, was not taken into account. This is because it is usually not feasible to replace HVAC and their distribution systems, especially in existing buildings, unless the savings is significant or the systems are too old. In the case of new buildings, if the system size can be reduced to match with reduced building load, payback periods will be shorter.

Table 35. Investment costs ($) for small houses in 16 cities.

Cities	Wall insulation	Roof insulation	Glazing	Wall, roof, glazing	Daylighting	Thermal Mass	Cooling	Heating	LPD	High efficiency appliance	Thermostat	Passive house	Zero energy building
Miami	4,563	1,524	7,747	13,834	1,549	3,615	414	600	29	1,680	-	19,033	16,557
Houston	4,183	1,524	7,747	13,454	1,549	3,615	322	750	29	1,680	-	18,653	16,235
Phoenix	4,183	1,524	7,747	13,454	1,549	3,615	460	550	29	1,680	-	18,653	16,173
Atlanta	4,183	1,524	7,747	13,454	1,549	3,615	345	750	29	1,680	-	18,653	16,258
Los Angeles	4,183	1,524	7,747	13,454	1,549	3,615	253	350	29	1,680	-	18,653	15,766
Las Vegas	4,183	1,524	7,747	13,454	1,549	3,615	414	550	29	1,680	-	18,653	16,127
San Francisco	4,183	1,524	7,747	13,454	1,549	3,615	276	450	29	1,680	-	18,653	15,889
Baltimore	4,183	1,033	7,747	12,963	1,549	3,615	276	600	29	1,680	-	18,162	15,548
Albuquerque	4,183	1,033	7,747	12,963	1,549	3,615	299	550	29	1,680	-	18,162	15,521
Seattle	4,183	1,033	7,747	12,963	1,549	3,615	253	500	29	1,680	-	18,162	15,425
Chicago	4,183	904	7,747	12,834	1,549	3,615	253	750	29	1,680	-	18,033	15,546
Chicago 24h	4,183	904	7,747	12,834	1,549	3,615	276	750	29	1,680	-	18,033	15,569
Denver	4,183	646	7,747	12,576	1,549	3,615	299	650	29	1,680	-	17,775	15,234
Minneapolis	2,423	646	7,747	10,816	1,549	3,615	207	750	29	1,680	-	16,014	13,482
Helena	2,423	646	7,747	10,816	1,549	3,615	253	700	29	1,680	-	16,014	13,478
Duluth	608	646	7,747	9,001	1,549	3,615	207	750	29	1,680	-	14,200	11,667
Fairbanks	608	646	7,747	9,001	1,549	3,615	207	1,000	29	1,680	-	14,200	11,917

Table 36. Investment costs ($) for medium office buildings in 16 cities.

Cities	Wall insulation	Roof insulation	Glazing	Wall, roof, glazing	Daylighting	Thermal mass	Cooling	Heating	Desk temp. reset	Thermostat setting	High efficiency appliance	Lighting power density	Zero energy building
Miami	16,092	25,694	321,170	362,955	64,234	140,731	17,480	9,100	-	-	69,647	6,661	465,842
Houston	16,092	25,694	321,170	362,955	64,234	140,731	16,652	9,350	-	-	69,647	6,661	465,264
Phoenix	16,092	25,694	321,170	362,955	64,234	140,731	18,101	6,950	-	-	69,647	6,661	464,313
Atlanta	16,092	25,694	321,170	362,955	64,234	140,731	15,801	5,300	-	-	69,647	6,661	460,363
Los Angeles	16,092	25,694	321,170	362,955	64,234	140,731	15,801	8,000	-	-	69,647	6,661	463,063
Las Vegas	16,092	25,694	321,170	362,955	64,234	140,731	17,710	8,100	-	-	69,647	6,661	465,072
San Francisco	16,092	25,694	321,170	362,955	64,234	140,731	16,905	6,850	-	-	69,647	6,661	463,017
Baltimore	13,835	25,694	321,170	360,698	64,234	140,731	17,342	12,750	-	-	69,647	6,661	467,097
Albuquerque	13,835	25,694	321,170	360,698	64,234	140,731	17,250	9,800	-	-	69,647	6,661	464,055
Seattle	13,835	25,694	321,170	360,698	64,234	140,731	16,859	7,700	-	-	69,647	6,661	461,564
Chicago	13,835	25,694	321,170	360,698	64,234	140,731	17,112	15,100	-	-	69,647	6,661	469,217
Chicago 24h	13,835	25,694	321,170	360,698	64,234	140,731	17,687	12,150	-	-	69,647	6,661	466,842
Denver	13,835	25,694	321,170	360,698	64,234	140,731	17,457	12,150	-	-	69,647	6,661	466,612
Minneapolis	13,835	25,694	321,170	360,698	64,234	140,731	17,043	16,950	-	-	69,647	6,661	470,998
Helena	13,835	25,694	321,170	360,698	64,234	140,731	17,089	16,150	-	-	69,647	6,661	470,244
Duluth	13,835	25,694	321,170	360,698	64,234	140,731	17,135	18,050	-	-	69,647	6,661	472,190
Fairbanks	13,835	25,694	321,170	360,698	64,234	140,731	16,790	20,250	-	-	69,647	6,661	474,045

Table 37. Investment costs ($) for factory buildings in 16 cities.

Cities	Wall insulation	Roof insulation	Glazing	Wall, roof, glazing	Daylighting	Thermal mass	Cooling	Heating	Desk temp. reset	Thermostat setting	High efficiency appliance	Lighting power density	Zero energy building
Miami	160,505	154,944	96,840	412,289	129,120	300,251	27,554	30,800	-	-	140,000	13,389	624,032
Houston	160,505	154,944	96,840	412,289	129,120	300,251	20,907	7,950	-	-	140,000	13,389	594,535
Phoenix	160,505	154,944	96,840	412,289	129,120	300,251	22,034	5,600	-	-	140,000	13,389	593,312
Atlanta	160,505	154,944	96,840	412,289	129,120	300,251	20,930	8,450	-	-	140,000	13,389	595,058
Los Angeles	160,505	154,944	96,840	412,289	129,120	300,251	19,987	3,750	-	-	140,000	13,389	589,415
Las Vegas	160,505	154,944	96,840	412,289	129,120	300,251	21,712	6,500	-	-	140,000	13,389	593,890
San Francisco	160,505	154,944	96,840	412,289	129,120	300,251	20,447	5,050	-	-	140,000	13,389	591,175
Baltimore	137,993	154,944	96,840	389,777	129,120	300,251	20,171	7,900	-	-	140,000	13,389	571,237
Albuquerque	137,993	154,944	96,840	389,777	129,120	300,251	20,332	6,500	-	-	140,000	13,389	569,998
Seattle	137,993	154,944	96,840	389,777	129,120	300,251	22,149	15,950	-	-	140,000	13,389	581,265
Chicago	137,993	154,944	96,840	389,777	129,120	300,251	20,079	9,800	-	-	140,000	13,389	573,045
Chicago 24h	137,993	154,944	96,840	389,777	129,120	300,251	21,551	10,000	-	-	140,000	13,389	564,717
Denver	137,993	154,944	96,840	389,777	129,120	300,251	20,217	7,950	-	-	140,000	13,389	571,333
Minneapolis	137,993	154,944	96,840	389,777	129,120	300,251	19,780	11,600	-	-	140,000	13,389	574,546
Helena	137,993	154,944	96,840	389,777	129,120	300,251	20,125	11,350	-	-	140,000	13,389	574,641
Duluth	137,993	154,944	96,840	389,777	129,120	300,251	19,527	12,150	-	-	140,000	13,389	574,843
Fairbanks	137,993	154,944	96,840	389,777	129,120	300,251	18,837	11,850	-	-	140,000	13,389	573,853

Performance of energy efficiency design strategies in terms of investment cost indicated in dollars per kilowatt-hour energy saving is shown in Table 38 and Table 39. The energy kilowatt-hour saving is calculated from total energy kilowatt-hour saving during each strategy's lifetime. The results are as follows:

- Decreasing lighting power density investment has the lowest cost per electricity saving ($/kWh) with less than 3 cents per kilowatt-hour saving.
- The highest investment costs per electricity saving strategies are daylighting in residential buildings because residential buildings are used mostly during night time. They also do not have deep interior spaces. Installing daylighting control systems do not benefit residential buildings much compared with their investment cost.
- Some strategies have lower investment cost per kilowatt-hour savings in colder climates, because heating loads can also be reduced. Strategies that are better in hotter climates are those that reduce building heating load or depend on solar radiation, such as daylighting, reducing lighting power density, using high performance appliances, and increasing cooling system efficiency.
- Increasing building insulation and glazing performance in already well-insulated ASHRAE compliant building can reduce heat entering building further. But at the same time, too much insulation can prevent heat from leaving building resulting in energy consumption increase in cooling systems. Suitable level of insulation and glazing performance varies from climate to climate. Negative values for investment cost per energy saving indicate that the strategies increase overall energy consumption compared with existing building energy which can be seen in using glazing with higher performance and the combination of increasing building insulation level with glazing performance.
- Setting the thermostat higher in winter and lower in summer has no investment cost because in ASHRAE complaint buildings, digital

thermostats are already installed and only proper settings are needed. Desk temperature reset is another strategy with no investment because of the similar reason. These two strategies provide free electricity saving through proper set up that does not affect thermal comfort inside buildings. However, desk temperature reset strategy is not applicable in small office buildings.

- In some cases, investment cost per electricity saving in Miami and Duluth are different from any other climate zones because Miami has only cooling load dominant while Duluth has only heating load dominant while other climate zones experience both cooling loads in summer and heating loads in winter. For example, thermal mass in Miami's residential buildings will trap heat and increase internal load. Even though, thermal mass can prevent heat entering buildings, the overall performance in reducing energy use in building is low, resulting in high investment cost per energy saving ($/kWh).

Table 38. Cost per watt energy savings ($/kWh) for energy efficiency design strategies in small and medium houses.

Cities	Wall insulation	Roof insulation	Glazing	Wall, roof, glazing	Daylighting	Thermal Mass	Cooling	Heating	Lighting power density	High efficiency appliance	Thermostat	Passive house	Zero energy building
Small Houses													
Miami	0.38	9.03	9.86	0.77	6.29	41.57	0.10	0.37	0.00	0.39	No Investment	0.36	0.27
Phoenix	0.15	2.34	-2.88	0.37	4.25	0.44	0.09	0.07	0.01	0.51		0.25	0.18
Las Vegas	0.11	1.13	-0.31	0.39	1.64	0.83	0.11	0.04	0.01	0.60		0.22	0.15
Baltimore	0.17	1.19	-0.35	0.71	2.22	-0.25	0.32	0.02	0.01	0.83		0.20	0.13
Chicago	0.14	0.97	-0.33	0.56	2.20	-0.17	0.50	0.02	0.01	0.89		0.17	0.11
Duluth	0.13	0.51	-0.56	-5.51	2.26	-0.10	2.09	0.01	0.14	4.88		0.13	0.07
Medium houses													
Miami	0.55	21.58	7.43	0.98	2.91	1.02	0.12	0.46	0.00	0.39	No Investment	0.35	0.28
Phoenix	0.17	3.81	-11.76	0.37	1.92	0.44	0.10	0.10	0.01	0.47		0.25	0.18
Las Vegas	0.12	1.41	-0.37	0.37	1.37	3.07	0.13	0.05	0.01	0.55		0.23	0.15
Baltimore	0.17	0.64	-0.40	0.65	1.67	-0.09	0.28	0.03	0.01	0.69		0.22	0.14
Chicago	0.14	0.99	-0.36	0.53	1.65	-0.06	0.36	0.03	0.01	0.75		0.20	0.13
Duluth	0.12	0.55	-0.79	13.08	2.04	-0.03	1.09	0.02	0.02	1.28		0.18	0.10

Table 39. Cost per watt energy savings ($/kWh) for energy efficiency design strategies in small, medium and big office buildings and factory buildings.

Cities	Wall insulation	Roof insulation	Glazing	Wall, roof, glazing	Daylighting	Thermal mass	Cooling	Heating	Desk temp. reset	Thermostat setting	High efficiency appliance	Lighting power density	Zero energy building
Small office buildings													
Miami	1.65	3.90	-10.47	4.65	0.09	0.27	0.03	0.80			0.24	0.01	0.28
Phoenix	0.62	0.83	-0.74	-18.04	0.10	0.27	0.04	0.09			0.29	0.01	0.28
Las Vegas	0.59	0.61	-4.31	1.58	0.08	15.40	0.06	0.04		No Investment	0.36	0.01	0.25
Baltimore	0.59	0.61	-4.31	1.58	0.08	15.40	0.06	0.04			0.36	0.01	0.25
Chicago	0.41	0.44	-0.70	-11.17	0.10	-0.83	0.09	0.03			0.45	0.02	0.27
Chicago 24h	0.14	0.15	-0.40	1.87	0.08	0.37	0.06	0.02			0.34	0.01	0.15
Duluth	0.30	0.32	0.95	0.81	0.13	-0.47	0.26	0.03			0.55	0.02	0.24
Medium office buildings													
Miami	1.17	0.63	4.23	2.98	0.18	0.98	0.02	1.24			0.12	0.01	0.18
Phoenix	0.16	0.23	-1.68	2.97	0.19	1.29	0.02	0.24			0.12	0.01	0.18
Las Vegas	0.19	0.25	-0.84	12.85	0.20	2.32	0.02	0.17			0.13	0.01	0.19
Baltimore	0.07	0.12	-2.08	0.81	0.14	0.32	0.03	0.05	No Investment	No Investment	0.17	0.02	0.16
Chicago	0.05	0.09	-0.86	-2.52	0.16	0.24	0.05	0.04			0.19	0.02	0.16
Chicago 24h	0.03	0.05	-1.10	-48.45	0.09	0.08	0.02	0.01			0.11	0.01	0.06
Duluth	0.03	0.06	0.53	-0.63	0.22	0.21	0.08	0.03			0.26	0.02	0.14
Big office buildings													
Miami	0.25	0.58	2.96	2.84	0.30	4.36	0.17	22.12			0.12	0.01	0.25
Phoenix	0.06	0.22	-13.67	2.92	0.33	8.12	0.29	1.53			0.13	0.01	0.29
Las Vegas	0.10	0.24	-7.64	4.44	0.33	-6.43	0.36	0.63			0.13	0.01	0.30
Baltimore	0.02	0.06	-5.44	4.95	0.20	0.79	0.36	0.08	No Investment	No Investment	0.16	0.02	0.26
Chicago	0.01	0.04	-1.60	-7.18	0.23	0.49	0.51	0.05			0.18	0.02	0.27
Chicago 24h	0.01	0.02	-0.88	-0.99	0.16	0.12	0.24	0.01			0.10	0.01	0.09
Duluth	0.01	0.02	1.14	0.44	0.32	0.30	0.82	0.03			0.24	0.03	0.27
Factory buildings													
Miami	1.35	1.43	-1.36	9.65	1.56	0.09	0.02	0.06			0.34	0.02	0.17
Phoenix	1.26	1.13	-1.08	9.07	1.45	0.18	0.02	0.02			0.34	0.02	0.19
Las Vegas	1.31	1.24	-0.94	4.57	1.67	0.15	0.03	0.01			0.36	0.02	0.19
Baltimore	1.28	1.37	-0.73	6.33	0.75	0.19	0.04	0.01	No Investment	No Investment	0.34	0.02	0.18
Chicago	1.52	1.64	-0.97	6.44	0.77	0.20	0.05	0.01			0.31	0.02	0.18
Chicago 24h	0.26	0.27	-0.38	0.69	0.54	0.08	0.02	0.01			0.14	0.01	0.08
Duluth	1.49	1.61	-0.47	6.69	0.93	0.24	0.10	0.01			0.35	0.02	0.18

For the analysis, total investment costs were used. The total investment costs are the sum of energy efficiency design strategies cost and PV systems cost. Electricity reductions were then calculated as electricity cost reduction by multiplying the reduction watt with state-average prices. Simple payback periods were then calculated by dividing total investment cost with annual electricity cost reduction. In this study, the investment cost did not include any incentives that were available and varied from location to location. Without incentives, investment costs appear to be very high and the payback period is very long because of the added PV systems cost.

4.1.4 Site energy and emission factors for building energy used.

To evaluate building energy performance, metrics such as total emission or source energy are sometimes used. Source energy refers to the primary energy used to generate and deliver the energy to the site. To calculate a building's total source energy, imported and exported energy is multiplied by the appropriate site-to-source conversion multipliers, such as 3.14 for electricity (Energy Information Administration, 2010a), or 3.2 for electricity and 1.07 for natural gas (Torcellini et al., 2006), or 3.34 for electricity and 1.047 for natural gas (Energy Star, 2009). To provide consistency in calculations, the DOE supports a research project to provide source energy conversion as well as emission factors of energy sources used in buildings (Deru & Torcellini, 2007). The factors for electricity are broken down by fuel type, and data is available for the entire country, state by state, and for the three grid interconnections. The energy used and emissions produced during extracting and transporting the fuels are also included. The following source conversion factors and emission factor were used in the calculations (Deru & Torcellini, 2007).

- Emission factor for delivered electricity is 0.758 kg of CO_{2e} /kWh of electricity.
- Emission factor for delivered natural gas is 0.043 kg of CO_{2e} /kWh (27.8 lb of CO_{2e} / MCF) of natural gas.
- Electricity site to source conversion factor is 3.365.
- Natural gas site to source conversion factor is 1.092.

4.1.5 Radar graph calculations.

Metrics performance in actual values and as percentages for small houses, medium office buildings, and factory buildings can be found in Appendix B. The radar graph was used for each energy efficiency design strategy to display performance in each metric at the same time (Figure 123). To produce radar graphs, the actual value of each metric from an energy efficiency design strategy was compared with its metrics' highest and lowest values. Equation (9) was used to calculate performance percentages for annual electricity reduction, peak load reduction, excess electricity reduction, investment cost reduction, payback period reduction, and site emission (Ton CO_{2e}) reduction. Equation (10) was used to calculate performance percentages for the percentage load met by PV.

$$\frac{M_{max} - M_{st}}{M_{max} - M_{min}} x\ 100\% \tag{9}$$

$$\frac{M_{st} - M_{min}}{M_{max} - M_{min}} x\ 100\% \tag{10}$$

Where

M_{max} = Metrics' maximum value.

M_{min} = Metrics' minimum value.

M_{st} = Strategy value.

A 100% represents the best performance and a 0% represents the worst performance in every metric displayed in radar graphs. In this study, there was no weighting applied to each metric. In an actual project, weighting factors according to emphasis on each metric can be applied to the percentage calculations. When comparing radar graphs produced from energy efficiency design strategies together, the graph with the largest area represents strategies that have the best overall performances.

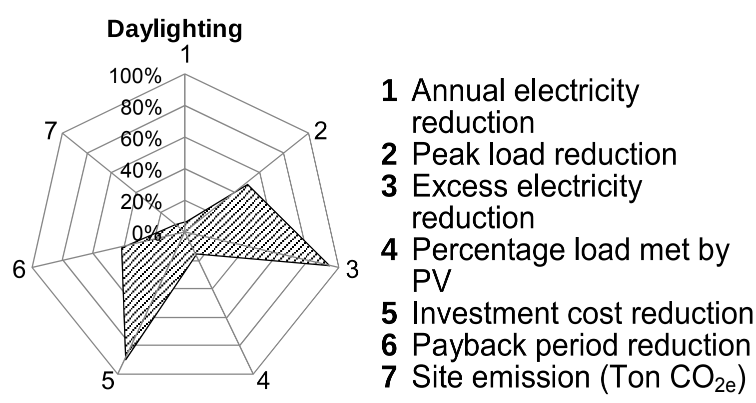


Figure 123. An example of a radar graph that represents seven performance metrics.

Each metric performance is typically an actual value from the strategy of interest compared with an actual value from existing buildings or ZEBs, because they usually give the maximum or minimum numbers. Existing building performances were used as base cases except for investment cost and payback period where ASHRAE-compliant building performances were used as base cases. This is because the investment costs are incremental costs from ASHRAE buildings (Section 4.1.3). Therefore, in radar charts for ASHRAE buildings, there is no value for investment cost reduction (no. 5) and payback period reduction (no. 6).

4.2 Discussion

ASHRAE-compliant buildings typically have the smallest patterned area, because energy efficiency design strategies were applied to ASHRAE buildings to help reduce energy use. The strategies with a smaller patterned area compared with ASHRAE-complaint buildings represent strategies that increase energy use in that building type and weather zone. Passive house and ZEBs typically have a large patterned area, because they have the highest performance in reducing energy use, increasing power load met, and reducing emission. The disadvantage of passive house and ZEBs is that they have the highest investment costs and produce the highest excess of electricity. However, their simple payback periods are short when compared with other energy efficiency design strategies.

Decreasing lighting power density is the best single strategy with high overall performance in all types of buildings and climates because of its ability to reduce electricity consumption, peak demand, and site CO_{2e} emission with low investment costs and a fast payback period. Other strategies, such as high efficiency appliances, cooling load efficiency, and daylighting, have high overall performances in specific conditions (Figure 124 - Figure 132).

Residential buildings

Miami

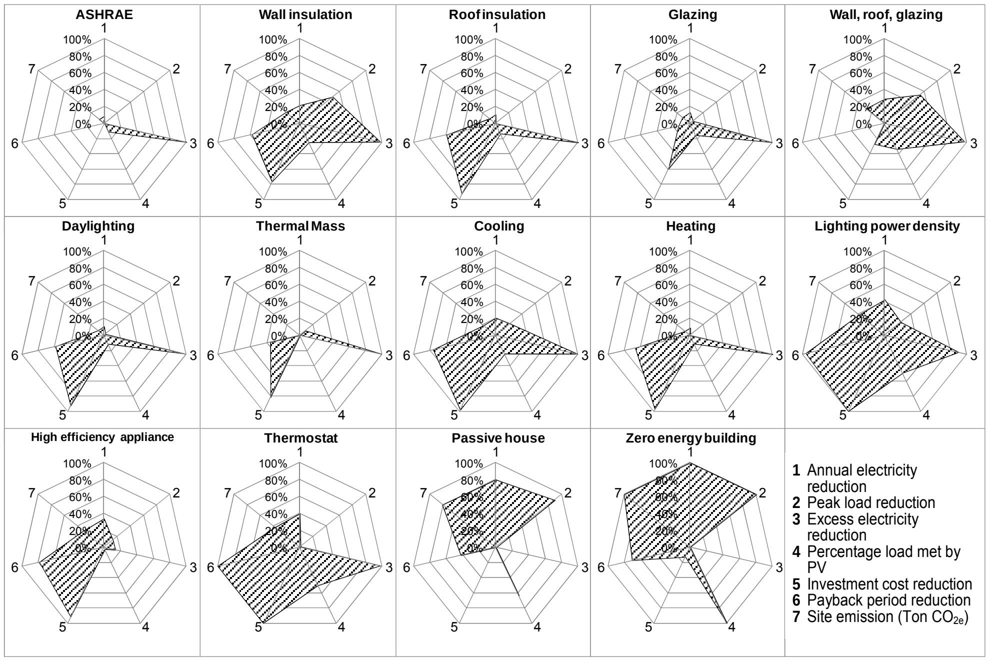


Figure 124. Performance metrics displayed in the form of radar charts for small houses in Miami.

Baltimore

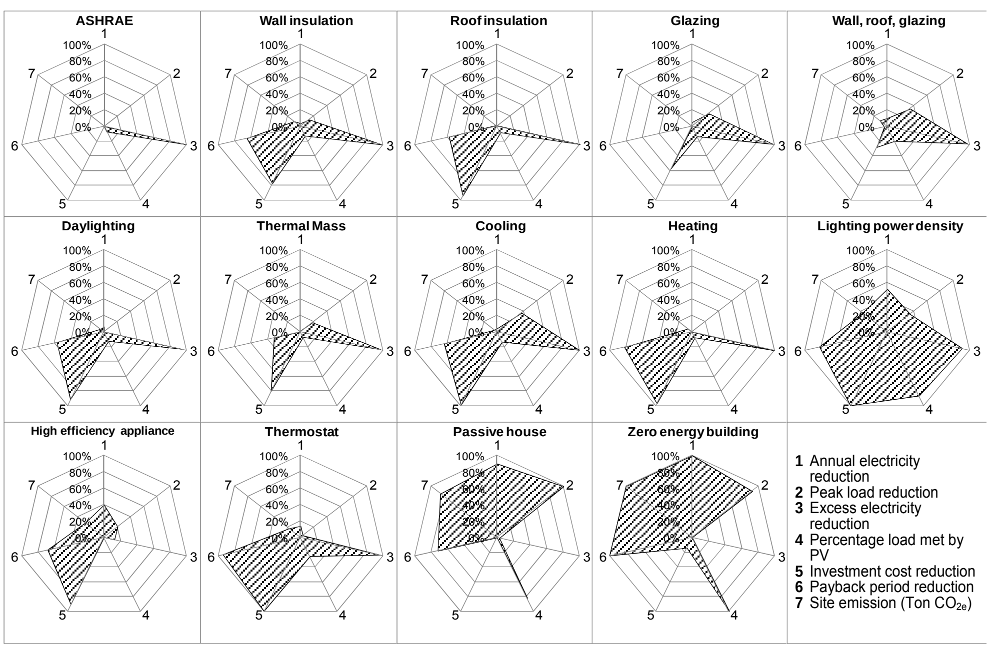


Figure 125. Performance metrics displayed in the form of radar charts for small houses in Baltimore.

Duluth

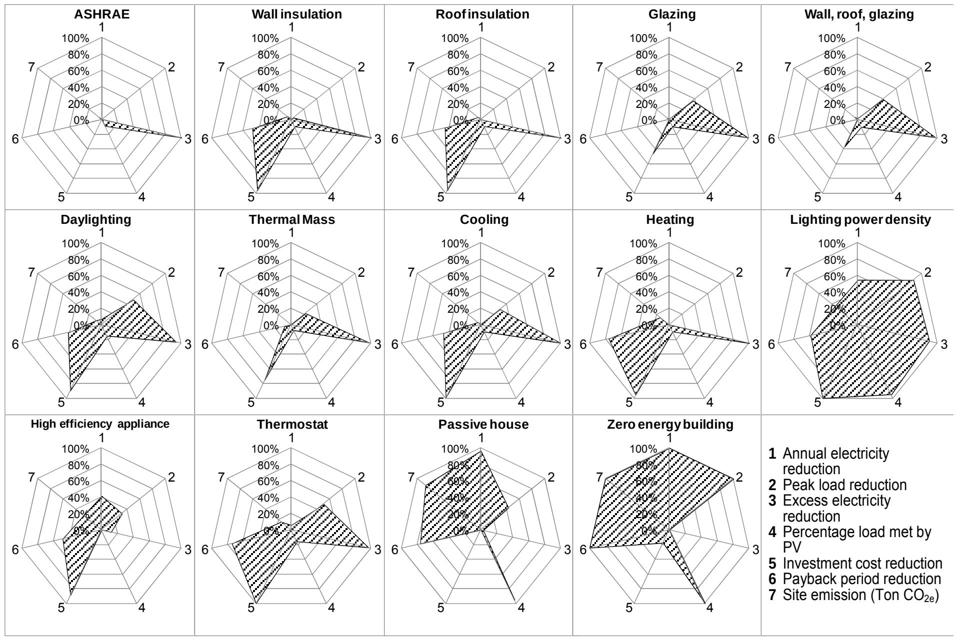


Figure 126. Performance metrics displayed in the form of radar charts for small houses in Duluth.

Commercial building

Miami

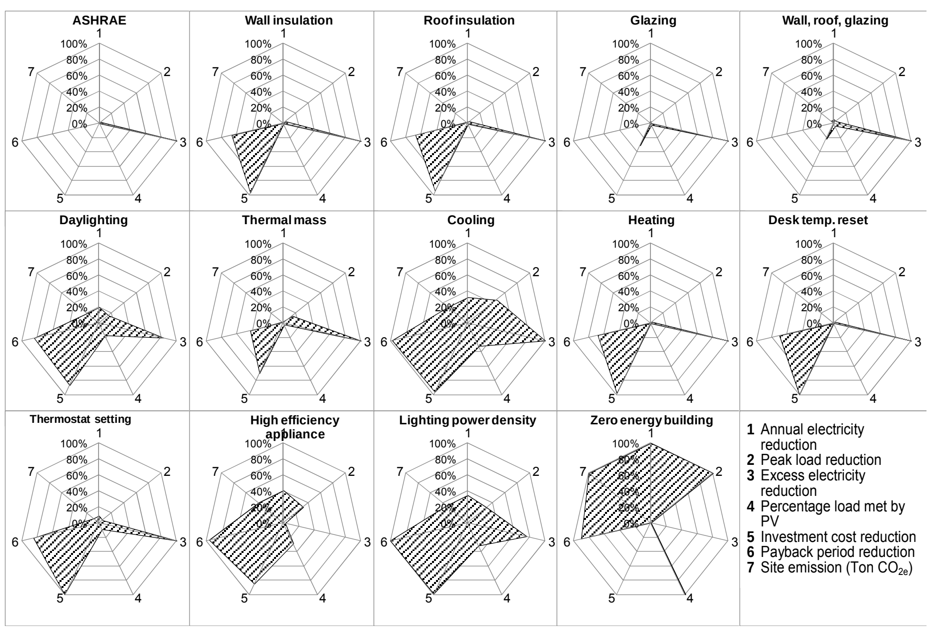


Figure 127. Performance metrics displayed in the form of radar charts for medium office buildings in Miami.

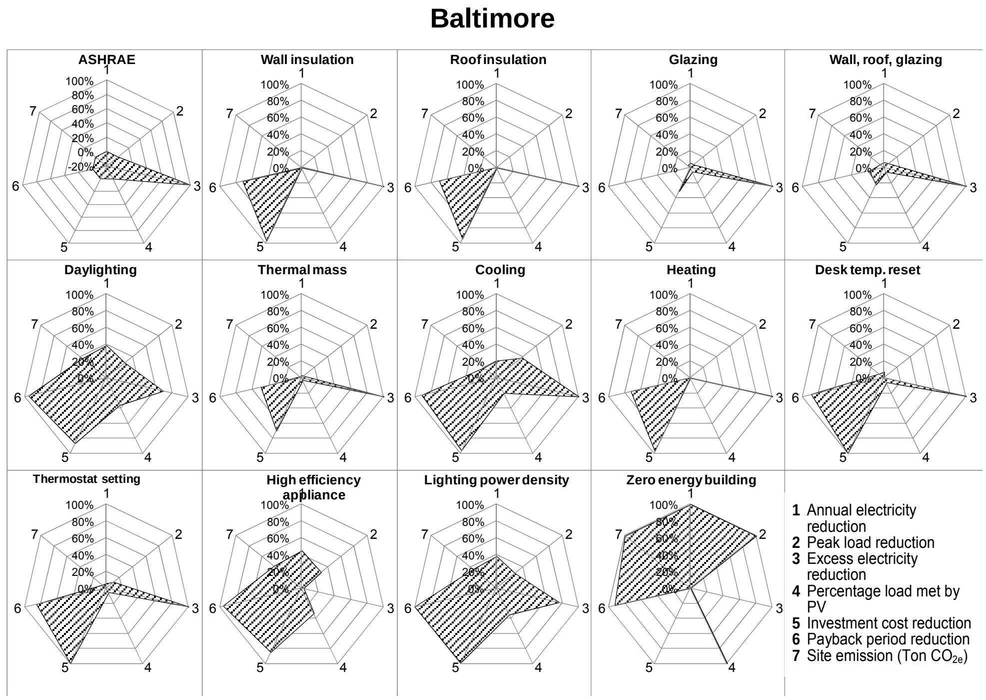


Figure 128. Performance metrics displayed in the form of radar charts for medium office buildings in Baltimore

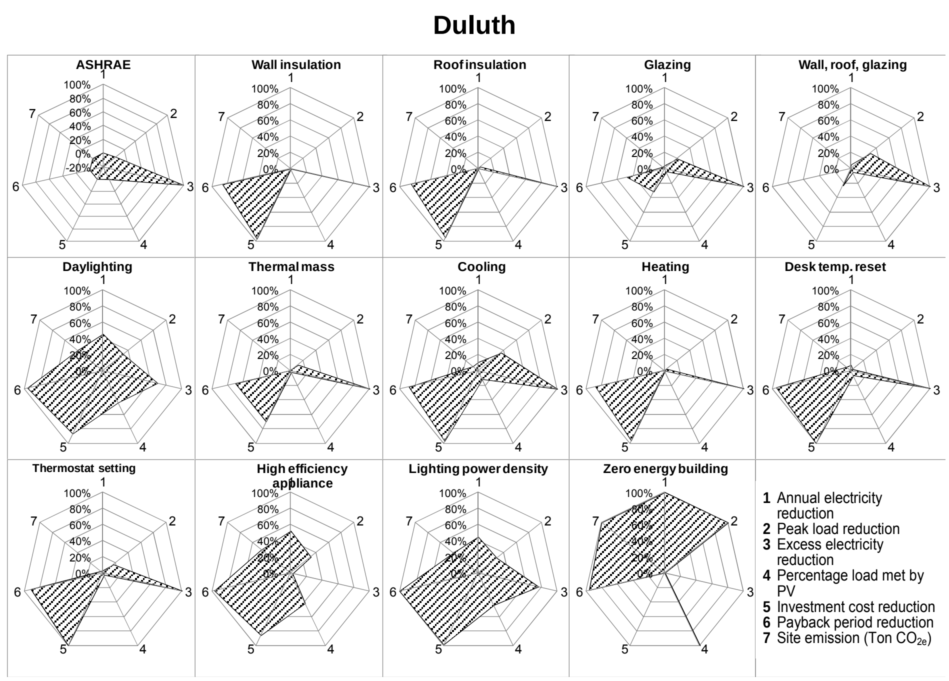


Figure 129. Performance metrics displayed in the form of radar charts for medium office buildings in Duluth.

Industrial buildings

Miami

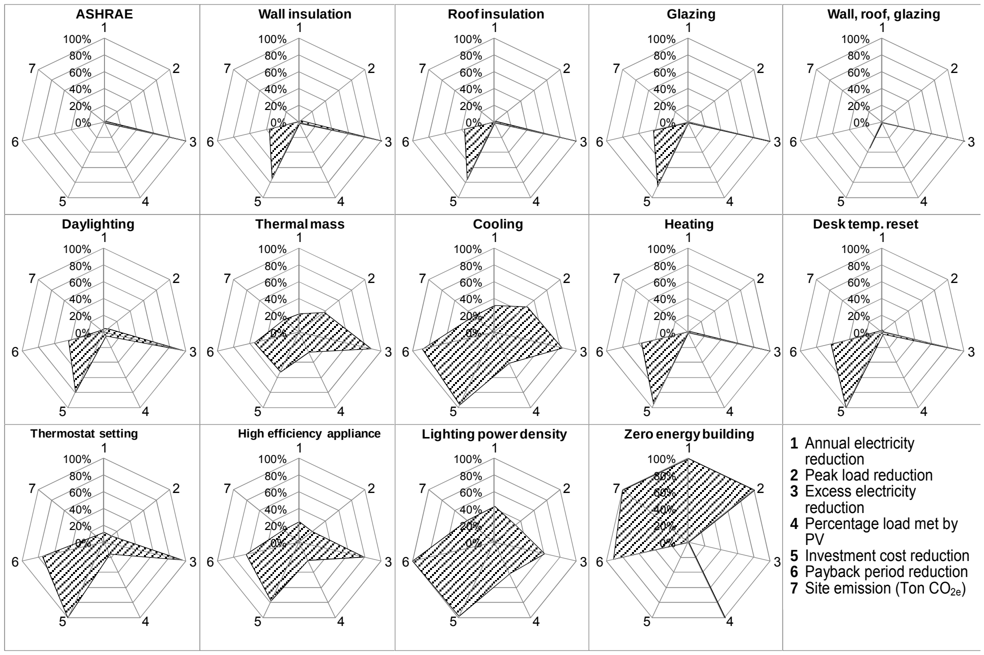


Figure 130. Performance metrics displayed in the form of radar charts for factory buildings in Miami.

Baltimore

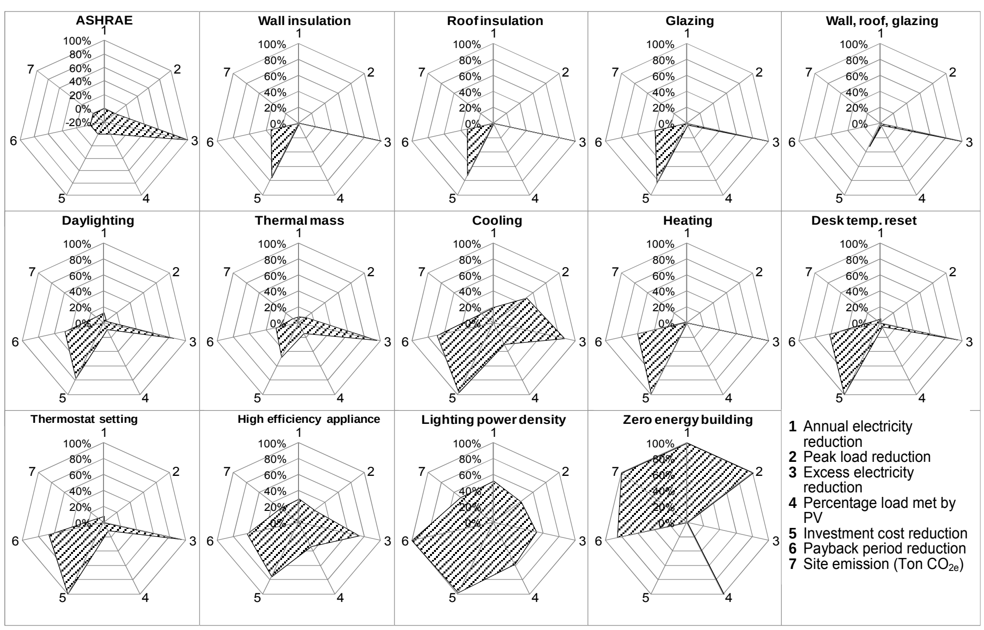


Figure 131. Performance metrics displayed in the form of radar charts for factory buildings in Baltimore.

Duluth

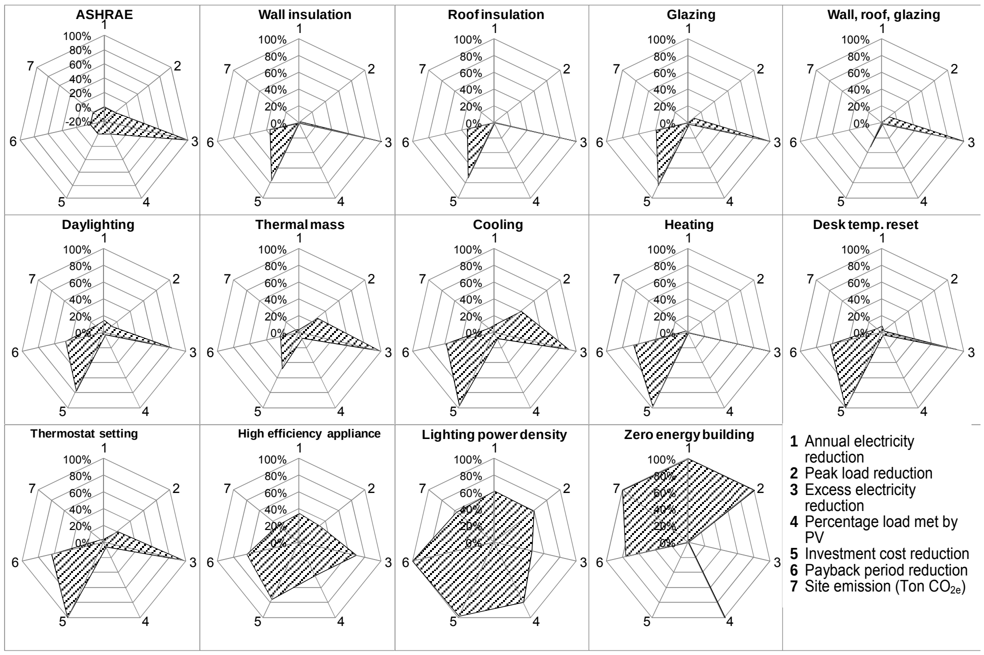
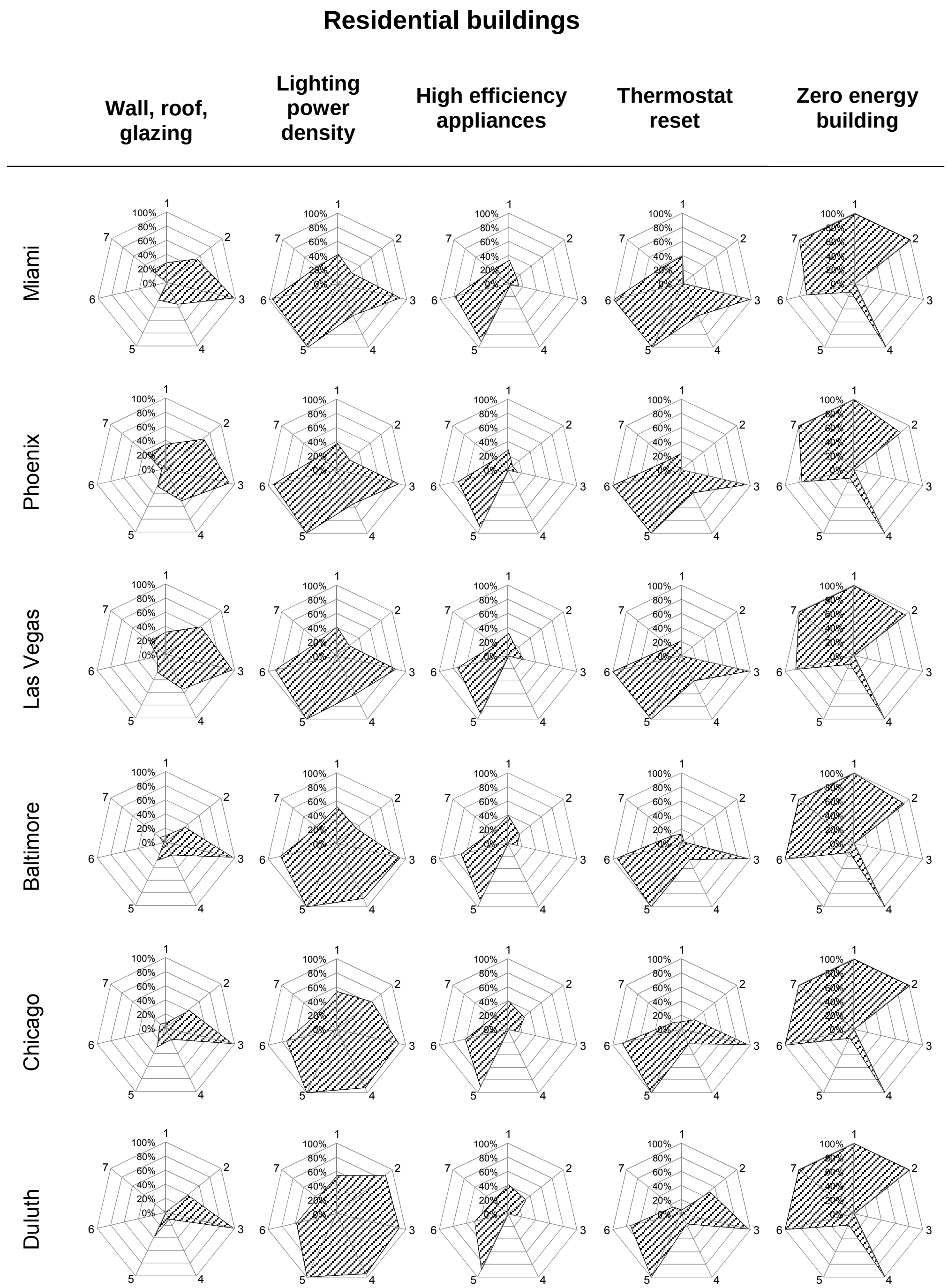


Figure 132. Performance metrics displayed in the form of radar charts for factory buildings in Duluth.

Figure 133 -Figure 135 compared the performance of five selected strategies in six different locations to demonstrate the impact of climate. In residential buildings, thermostat reset, increasing wall insulation, and cooling system efficiency are strategies with good overall performance in hot and mild climates. In cold climates, daylighting, and thermostat reset are good strategies.

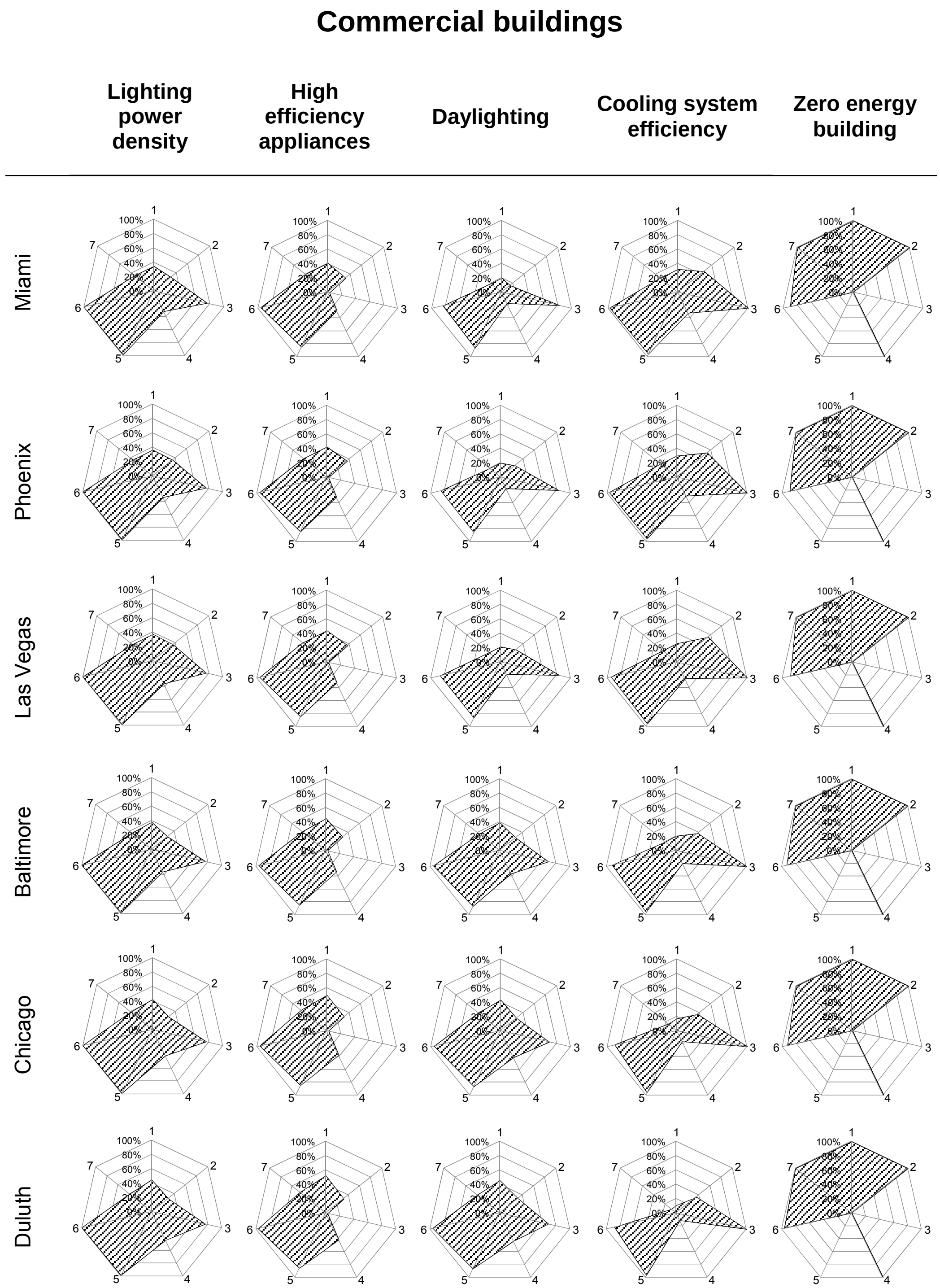
In commercial buildings, cooling strategy has a good overall performance in hot climates, while daylighting and high efficiency appliances strategies have a good overall performance in mild and cold climates.

In industrial buildings, cooling strategy has a good overall performance in hot climates, while the high efficiency appliances strategy has a good overall performance in mild and cold climates.



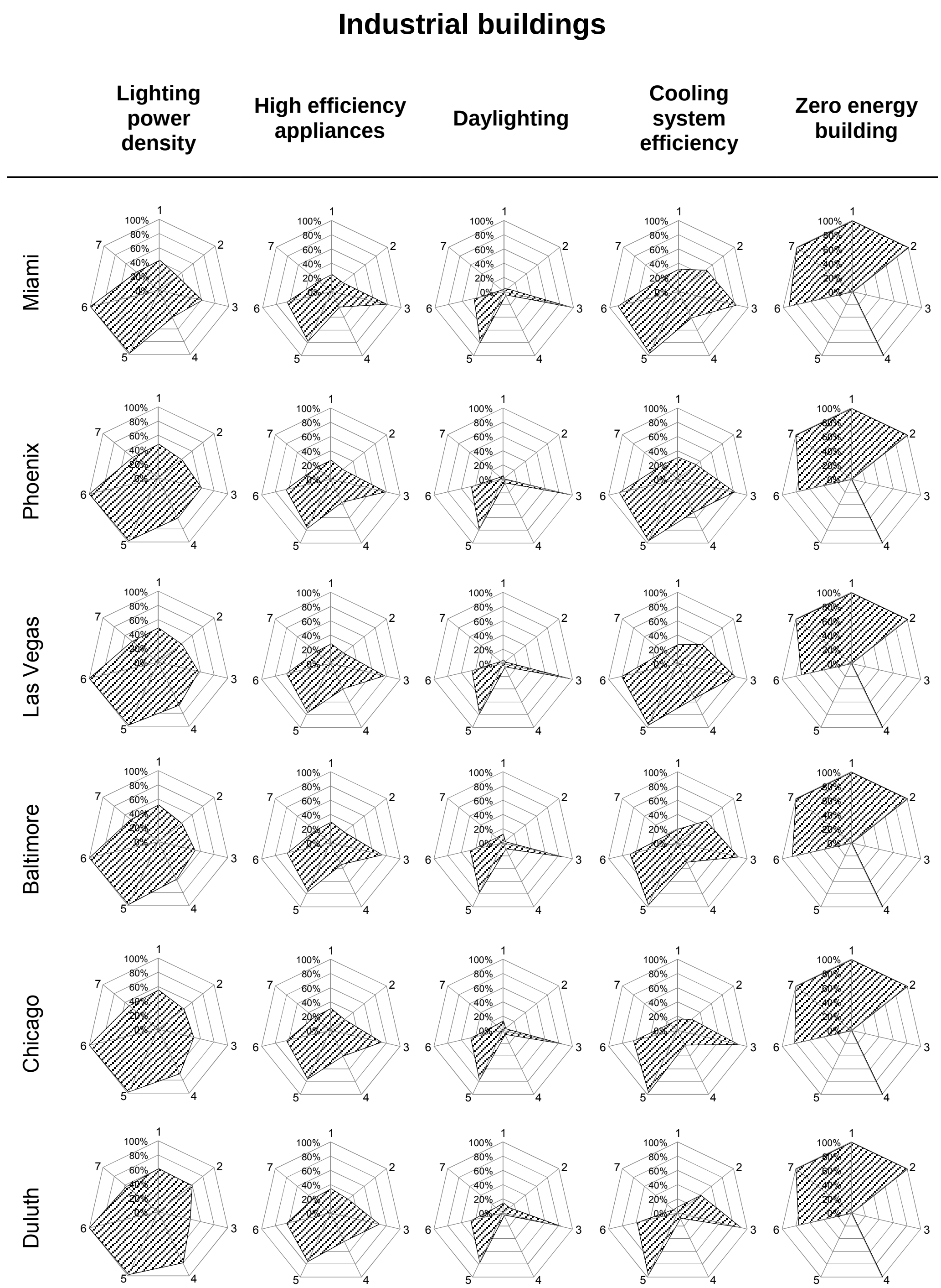
1. Annual electricity reduction
2. Peak load reduction
3. Excess electricity reduction
4. Percentage load met by PV
5. Investment cost reduction
6. Payback period reduction
7. Site emission (Ton CO_{2e})

Figure 133. Performance metric comparisons of five selected strategies in small houses located in six cities.



1. Annual electricity reduction
2. Peak load reduction
3. Excess electricity reduction
4. Percentage load met by PV
5. Investment cost reduction
6. Payback period reduction
7. Site emission (Ton CO_{2e})

Figure 134. Performance metric comparisons of five selected strategies in medium office buildings located in six cities.



1. Annual electricity reduction
2. Peak load reduction
3. Excess electricity reduction
4. Percentage load met by PV
5. Investment cost reduction
6. Payback period reduction
7. Site emission (Ton CO_{2e})

Figure 135. Performance metric comparisons of five selected strategies in factory buildings located in six cities.

CHAPTER 5
CONCLUSIONS AND FUTURE WORKS

5.1 Conclusions

There are few studies that look at energy efficiency design strategies and grid-connected PV systems as the integration of electricity efficiency measures. This study investigated the potential and relationships of energy efficiency design strategies and grid-connected PV systems implemented together in residential, commercial, and industrial buildings. Computer modeling of residential, commercial, and industrial buildings (small houses, medium houses, small office buildings, medium office buildings, big office buildings, and factory buildings) implemented energy efficiency design strategies, and grid-connected PV systems was conducted. Building energy consumption characteristics and electricity output from grid-connected PV systems were examined. The impact of building sizes and use patterns as well as climate conditions in 16 cities were also investigated. With large databases of various building energy use conditions available from the simulations, this study allowed the analysis of buildings both as an individual building and as a community or a cluster of buildings. The conclusions of this study are:

1. **Energy use characteristics**

   Different typical architecture characteristics result in different energy use behavior in different building types (Figure 136). Climate is another major factor impacting energy use characteristics in buildings. Sixteen cities—Miami, Houston, Phoenix, Atlanta, Los Angeles, Las Vegas, San Francisco, Baltimore, Albuquerque, Seattle, Chicago, Denver, Minneapolis, Helena, Duluth, and Fairbanks – representing all U.S. climate zones – were used in the simulations to show local weather impact. Residential building energy use largely depends on external weather, because its proportion of envelope area to floor area is high. The majority of energy use is for space heating; therefore, buildings in cold climates use more energy than buildings in hot climates. However, the energy source for heating systems is mostly natural gas. For electricity consumption, building appliances and lighting systems share the largest electricity use proportion. Commercial buildings and industrial buildings (excluding process loads) use electricity more than natural gas, except for buildings in very cold climates. Because the envelop area to building floor areas is small, energy use is mostly from internal loads, such as lighting, appliances, and equipment for commercial buildings and lighting for industrial buildings.

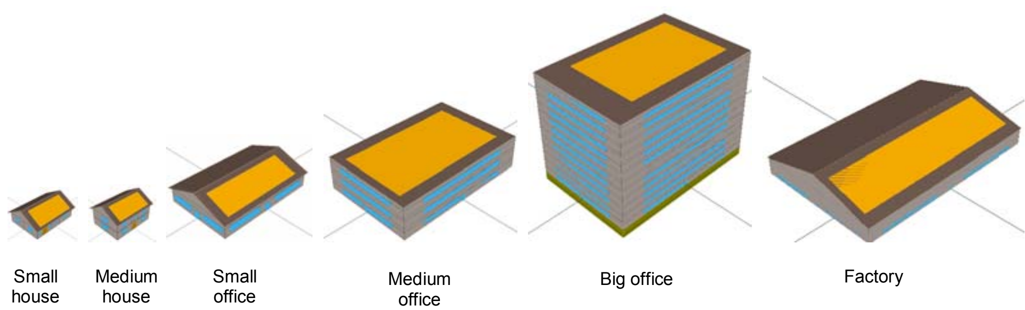


Figure 136. Six building types used in the simulations (not to scale).

2. **ASHRAE-compliant buildings potential compared with existing buildings**

Energy reduction potential

- For residential buildings, compliance with ASHRAE 90.1-2007 and ASHRAE 90.2-2007 standards can reduce energy consumption approximately 27% in cold climates and up to 44% in hot climates. The percentage number is higher in hotter climates. However, energy consumption in buildings in hotter climates is lower.
- For commercial buildings, compliance with ASHRAE standards can reduce energy consumption approximately 14% in hot climates and up

to 22% in cold climates. The percentage number is higher in colder climates.

- For industrial buildings, compliance with ASHRAE standards can reduce energy consumption range from approximately 16% in hot climates to 29% in cold climates. The percentage number is higher in colder climates.

Electricity reduction potential

- Electricity consumption can be reduced approximately 21% to 51% in residential buildings, 13% to 17% in commercial buildings, and 20% to 23% in industrial buildings.
- Peak electricity demand reductions were approximately 43% to 51% in residential buildings and approximately 12% to 28% in commercial and industrial buildings.

3. Grid-connected PV systems potential:

Available roof spaces for PV systems installation in buildings are the consequence of the architectural characteristics of each building type. Residential buildings have enough roof area to accommodate a PV system that, with careful design, can meet building electricity consumption. Commercial buildings usually have many floors, and the roof areas available are not sufficient to accommodate a PV system size that can meet the high electricity demands of these buildings. Industrial buildings usually have high electricity demands and large roof area available. If funding is available for investment, the available roof area can accommodate the PV system size that will meet the building electricity demand. Grid-connected PV sizes used in the simulations are shown in Table 40. The percentage of PV electricity output compared with building electricity demand in Miami, Phoenix, Las Vegas, Baltimore, Chicago, and Duluth are shown in Table 41.

Table 40. Grid-connected PV sizes in each building type used in simulations.

Building type	Typical size PV (kW DC)	Full roof size PV (kW DC)	Full roof with parking roof size PV (kW DC)
Small/medium houses	4	10	-
Small office buildings	20	50	-
Medium office buildings	30	168	225
Big office buildings	100	342	684
Factory buildings	500	1000	1057

Table 41. Grid-connected PV electricity outputs in each building type compared with their building electricity demand in Miami, Phoenix, Las Vegas, Baltimore, Chicago, and Duluth.

Building types	Electricity output from typical size PV systems		Electricity output from Full roof with parking roof size PV systems	
	% Building annual electricity consumption	% Building peak demand	% Building annual electricity consumption	% Building peak demand
Small houses	41%-68%	54%-73%	117%-194%	100%-207%
Medium houses	23%-36%	32%-39%	65%-102%	68%-112%
Small office buildings	48%-58%	44%-68%	120%-137%	111%-169%
Medium office buildings	4%-5%	6%-7%	29%-36%	45%-58%
Big office buildings	1%-2%	3%	10%-13%	18%-20%
Factory buildings (exclude process load)	53%-65%	71%-84%	112%-138%	151%-177%

4. Ranking of energy efficiency design strategies in buildings with grid-connected PV systems in reducing annual electricity consumption

Energy efficiency design strategies investigated in residential, commercial, and industrial buildings are listed in section 2.4.4. More details of each strategy can be found in section 2.3.

- Applying these strategies to ASHRAE-compliant buildings could further reduce electricity consumption further up to 30% in residential buildings and up to 25% in commercial and industrial buildings by the combination of strategies such as passive house and ZEB.
- Small houses can achieve zero electricity consumption with the ZEB strategy and PV 4 kW size systems.
- The percentage numbers of electricity reduction were higher in colder climates and in 24-hour use buildings.
- The first and second best single energy efficiency design strategies in each type of building are listed in Table 42.

Table 42. Best single strategies in reducing annual electricity consumption for residential, commercial, and industrail buildings in six cities.

Building types	Ranking	Miami	Phoenix	Las Vegas	Baltimore	Chicago	Duluth
Small houses	**1.**	**Lighting power density (LPD)**					
	2.	Thermo stat reset	Envelope performance: Wall, roof, glazing	High efficiency appliances			
Medium houses	**1.**	**Lighting power density (LPD)**					
	2.	High efficiency appliances	Envelope performance: Wall, roof, glazing	High efficiency appliances			
Small office buildings	**1.**	**Daylighting**					
	2.	Lighting power density (LPD)					
Medium office buildings	**1.**	**High efficiency appliances**					
	2.	Lighting power density (LPD)			Daylighting		
Big office buildings	**1.**	**High efficiency appliances**					
	2.	Lighting power density (LPD)					
Factory buildings	**1.**	**Lighting power density (LPD)**					
	2.	Cooling system efficiency			High efficiency appliances		

- The proportion of electricity savings increased in residential buildings with 24-hour use schedule compared with electricity proportion in normal use schedule buildings. However, in commercial and industrial buildings, the impacts from use schedule on electricity savings were small.

5. **Ranking of energy efficiency design strategies in buildings with grid-connected PV systems in reducing peak electricity demand:**

- For peak electricity demand reduction, ZEB strategy was the best strategy in all kinds of buildings.

- The first and second best single energy efficiency design strategies in each type of building are listed in Table 43.

Table 43. Best single strategies in reducing peak electricity demand for residential, commercial, and industrail buildings in six cities.

Building types	**Miami**	**Phoenix**	**Las Vegas**	**Baltimore**	**Chicago**	**Duluth**
Small houses	Envelope performance: Wall, roof, glazing			Cooling systems efficiency	Lighting power density (LPD)	
Medium houses	Envelope performance: Wall, roof, glazing			Lighting power density (LPD)		Thermal mass
Small office buildings	Cooling systems efficiency			Daylighting		
Medium office buildings	Cooling systems efficiency					Cooling systems efficiency and daylighting
Big office buildings	High efficiency appliances					
Factory buildings	Cooling systems efficiency					

- Grid-connected PV systems have more benefits in summer in reducing peak electricity demand than in winter because the days are longer and peak electricity demand are higher.

- The peak electricity demand reduction percentage numbers increased with colder climates and the proportion of PV system size to building electricity loads.
- Peak electricity demand reduction percentage numbers when energy efficiency design strategies and grid-connected PV systems were implemented together were less than implementing them separately because peak electricity demand is reduced at different time periods.

6. Excess electricity and electricity load met:

- ZEB is the best strategy for increasing building electricity load met in all building types. However, it also results in the highest excess of electricity.
- In residential buildings, reducing lighting power density is the best single strategy that can increase load met percentages.
- In commercial buildings, reducing lighting power density and increasing cooling system efficiency are the best single strategies.
- In industrial buildings, reducing lighting power density, increasing cooling system efficiency, and thermal mass are the best single strategies.
- Excess electricity in buildings is higher in winter than in summer.
- PV systems that are larger in size can increase load met percentages, but if the system is too large, excess electricity will also increase.

7. Potential of electricity reduction in clusters of buildings:

Available databases of residential, commercial, and industrial buildings implementing energy efficiency design strategies and grid-connected PV systems in 16 climates allow opportunities for electric utility companies to explore different options in implementing PV systems with energy efficiency design strategy options applicable to typical buildings. Various energy efficiency design strategies, grid-connected PV systems, and building types and building number combinations can be studied and electricity savings can be predicted. Examples can be found in sections 3.3.4.

8. Analysis metric results

In evaluating design options for decision making, many variables can be considered. Electricity use reduction (building annual electricity consumption reduction and building peak electricity demand reduction), impact to the electric grids (excess PV electricity output and building electricity load met), financial analysis (investment cost, simple payback period) and greenhouse gas emission (site CO_{2e} emission) were selected as performance metrics for each energy efficiency design strategy implemented in buildings with grid-connected PV systems.

ASHRAE-compliant buildings generally have the lowest overall performances because they are used as base cases. Generally, ZEBs have highest overall performances in all kinds of buildings. ZEBs have the highest electricity consumption reduction and highest peak electricity reduction, which lead to the highest site emission reduction. They also have the highest percentage load power met compared with electricity demand. The disadvantage of implementing ZEBs is that they have the highest investment cost and the highest excess electricity. However, the payback periods are not long. Decreasing lighting power density (LPD) is a single strategy that has the highest overall performance in all types of buildings. It is ranked number one or two among single strategies in reducing electricity demand in most types of buildings. The LPD investment cost is low and results in a fast payback period. Other good performance strategies include:

- Residential buildings in hot and mild climates: thermostat reset, increasing wall insulation and cooling system efficiency.
- Residential buildings in cold climates: daylighting and thermostat reset.

- Commercial buildings in hot climates: cooling system efficiency.
- Commercial buildings in mild and cold climates: daylighting strategy and high efficiency appliances.
- Industrial buildings in hot climates: cooling system efficiency.
- Industrial buildings in mild and cold climates: high efficiency appliances strategy.

5.2 Contributions

1. This study presented the performance of energy efficient design strategies that are applicable to groups of residential, commercial, and industrial buildings with grid-connected PV systems in 16 climate zones. Electricity use behavior of different building types and use schedules in different climates provide a broad understanding of the impact of implementing energy efficiency design strategies in buildings with grid-connected PV systems in various conditions. These data can be used as guidelines for energy efficiency design strategies selection for each building type in each climate condition to meet different goals.
2. The results can assist building owners in selecting the best energy efficiency design strategies that fit their objectives and budgets. Electric utility companies can use the results in evaluating future PV interconnection applications and in planning future network protection system upgrades.
3. A better understanding of how PV electricity output interacts with building electricity use pattern behavior can lead to efficient management of this type of energy source.
4. Available databases of residential, commercial, and industrial buildings implementing energy efficiency design strategies and PV systems in 16 climates provides opportunities for governments and electric utility companies to explore different options in implementing PV systems with energy efficiency design strategies to groups of buildings. A series of predictive models could be generated to examine the possible scenarios

by a utility's power distribution engineers and planners. Weather data, customer end use behavior at a time or season, and the grouping of various sectors could be easily tested. Each predictive model could be updated in accordance to the local condition, including electricity rate structures. These studies are necessary for future policy planning by government and electric utility companies according to the transition from traditional electric grid systems to smart grid systems.

5.3 Future Works

The studies reported in this dissertation are sufficient to provide insight into energy efficiency design strategy options in buildings with grid-connected PV systems. However, there are several options for future work that could provide more understanding of the interaction between energy efficiency design strategies and electricity output from grid-connected PV systems as well as the impact to the electric grids. Suggested future work includes:

1. Sensitivity analysis of databases could be further studied to determine the uncertainty of results for given input ranges or changes.
2. Validation studies using actual case studies in real contexts and satellite derived weather data could lead to modeling updates to match real conditions as much as possible.
3. This study was conducted with recorded weather data. Future performance could be studied using weather data generated with global warming effect predictions.
4. The reduction of HVAC system size, which could be implemented when there is reduced load as a result of improving building envelope or reducing lighting and appliance load, was not taken into account in this study. Further studies could investigate the synergy potential of load reduction and HVAC equipment size reduction when major renovation is required or a new building is constructed.

5. Detailed investigation of reducing energy use in appliances in commercial buildings and reducing process loads in industrial buildings should be studied, because they a have high impact on the largest energy consumption categories.
6. Energy use predictive models based on substantial databases, including building types (residential, commercial, and industrial) of varying size and energy use patterns, could be generated to reduce the electric grid system's stress during peak demand by engineers and planners from electric utility companies who are responsible for power distribution, given local climatic condition and energy demand priorities.
7. The evolution of a smart grid system enables better communication between PV systems and utility distribution systems management. This evolution also solves some technical challenges in transmission and distribution systems, which would allow more PV systems penetration. With the availability of real-time satellite derived weather data and the database from this study, interactive management scenarios could be generated and evaluated.
8. Proper grid-connected PV size should be further investigated to find the proper size for each building type and size located in each climate that could benefit both building owners and electricity utility companies.

Clearly, future studies concerning design strategies and their relevance to grid-connected PV systems should focus on real-time weather data, global warming effects, predictive modeling using large databases, new innovations in smart-grid systems, and correctly matching the grid-connected PV size with the appropriate building type and size. Innovation and progress in energy efficiency design strategies will not only benefit the owners and occupants of our built world, but will lead the way to a cleaner and healthier environment.

APPENDIX A

ASHRAE-COMPLIANT MODEL INPUTS IN eQUEST

Table 44. Residential building ASHRAE-compliant model inputs in eQUEST (All inputs displayed here in IP unit).

Item	Details	References
Project type	Multifamily, low-rise (exterior entries)	
Location	User selected: 16 cities	
Analysis year	2010	
Geometry	**Small house** 1,200 ft^2 1 story **Medium house** 2,400 ft^2 2 stories Aspect ratio: 1.33 Foot print: 30 ft x 40 ft Floor to floor: 9.0 ft Floor to ceiling: 8.0 ft	2003 EIA survey
Roof	Pitched roof 30° tilted with 2' overhang Construction layers • Shingle roof • Wood standard frame • Air space • Insulation o Houston, Phoenix, Atlanta, Los Angeles, Las Vegas, San Francisco R-25 (U= 0.034) o Baltimore, Albuquerque, Seattle R-36 (U= 0.025) o Chicago, Denver R-40 (U= 0.022) o Minneapolis, Helena, Duluth R-44 (U= 0.021) o Fairbanks R-47 (U= 0.020) Roof exterior absorptance 0.2 (White-lacquer)	ASHRAE 90.2-2007 U-Ceiling with attic • Miami = not required • Houston, Phoenix, Atlanta, Los Angeles, Las Vegas, San Francisco = 0.036 • Baltimore, Albuquerque, Seattle = 0.026 • Chicago, Denver = 0.023 • Minneapolis, Helena, Duluth = 0.021 • Fairbanks = 0.020 Absorptivity 0.2

Item	Details	References

Wall	Construction layers
	• Wood frame 2x6, 16 in o.c.
	• Wood/plywood
	• 1 in polystyrene (R4)
	• Insulation
	  o Miami R-0 (U= 0.089)
	  o Houston, Phoenix, Atlanta, Los Angeles, Las Vegas, San Francisco R-4 (U= 0.075)
	  o Baltimore, Albuquerque, Seattle, Chicago, Denver R-6 (U= 0.055)
	  o Minneapolis, Helena R-23 (U= 0.040)
	  o Duluth, Fairbanks R-28 (U= 0.034)
	Wall exterior absorptance 0.5 (Green-light)
		ASHRAE 90.2-2007
		U Wood – Cavity
		• Miami = 0.089
		• Houston, Phoenix, Atlanta, Los Angeles, Las Vegas, San Francisco = 0.083
		• Baltimore, Albuquerque, Seattle, Chicago, Denver = 0.058,
		• Minneapolis, Helena = 0.044
		• Duluth, Fairbanks = 0.035
		
		Absorptivity 0.2

Ground floor	Construction layers • Earth contact • 6 in concrete • Carpet with fiber pad • Vertical exterior board, R-10, 4 ft deep	ASHRAE 90.2-2007 Slab on grade – no requirement
Infiltration	Perim: 0.038 CFM/ft^2 (ext. wall area) Core: 0.001 CFM/ft^2 (floor area)	eQUEST default
Interior: top floor ceilings	Construction layers • Drywall finish • Wood standard framing • No insulation	ASHRAE 90.2-2007 Top floor ceiling – no requirement
Interior: ceilings	Construction layers • Drywall finish • No insulation	eQUEST default
Interior: vertical walls	Construction layers • Frame • No insulation	eQUEST default
Door	1 door at northern orientation 6.7 ft x 6 ft Wood, solid core flush, 1 3/8 in	ASHRAE 90.1-2007 One 40 ft^2 opaque wood door facing north for each living unit
Exterior window	Miami, Houston, Phoenix Single Pilkington Eclipse Adv Evergreen 6 mm (Code 5853): U=0.67, SHGC = 0.36, VT = 0.48 Atlanta	ASHRAE 90.2-2007 Equal area in each direction Assumed internal shading to reduce SC

Item	Details	References
	Double Pilkington Arctic Blue/Air/Clear 6 mm (Code 6841): U=0.47, SHGC = 0.39, VT = 0.47 Los Angeles, Las Vegas, San Francisco, Baltimore, Albuquerque, Seattle, Chicago, Denver, Minneapolis, Helena, Duluth, Fairbanks Double guardian Sun-guard LE63 Clear/Air/Clear 6mm (Code 6451): U=0.35, SHGC = 0.51, VT = 0.62 Frame insulation fiberglass/vinyl, operable, MTL spacer 1.5 in width Window height 4.25 ft, sill 3.00 ft 15% wall area each direction No overhang, no fin Fabric Drapes – Light color 20% closed when occupied 80% closed when unoccupied	by 30% No outside shading U Miami, Houston, Phoenix = 0.67 Atlanta = 0.47 Los Angeles, Las Vegas, San Francisco, Baltimore, Albuquerque, Seattle, Chicago, Denver, Minneapolis, Helena, Duluth, Fairbanks = 0.35 SHGC Miami, Houston, Phoenix = 0.37 Atlanta = 0.40 Los Angeles, Las Vegas, San Francisco, Baltimore, Albuquerque, Seattle, Chicago, Denver, Minneapolis, Helena, Duluth, Fairbanks = NR
Building operation schedule	Daytime unoccupied, typical use Weekdays 5 pm-7 am Weekend 4 pm-9 am	eQUEST default
Activity areas allocation	**Space % ft^2/per CFM/per** Bedroom 40 624 50 General living space 60 624 50	eQUEST default
Zone group	2 zones: general living space and bed room	
Interior lighting	0.5 W/ft^2	ASHRAE 90.1-2007 Table 9.6.1
Misc. load	0.2 W/ft^2	
Domestic hot water	Model DHW Equipment with seasonal profile	eQUEST default
Laundry facilities	In-unit, one unit/floor 10.1 loads/unit/week Washer type: vertical axis, use electricity	eQUEST default
HVAC System 1	Cooling source: DX Coil Heating source: furnace	ASHRAE 90.2-2007 Air source heat pump

Item	Details	References
	System type: split system single zone DX with furnace (residential) 1 system/zone Return air: ducted Thermostat setpoint • Occupied Cool: 78°F, heat 68°F • Unoccupied Cool: 85°F, heat 60°F Design temperature • Cooling: indoor 75°F, supply 55°F • Heating: indoor 72°F, supply 120°F Air flow: min design flow 0.5 CFM/ft^2 VAV minimum flow: 100% Cooling: Auto-size, < 65 kBtuh or 5.4 tons Air-cooled, SEER = 14.5 Allow crankcase heating Heating: auto-size, < 225 kBtuh AFUE = 0.90 Supply fan: power 1.00 in. WG High efficiency Auto-size flow (with 1.15 safety factor) Variable speed drive Fan schedule: no fan night cycle fan on mode = intermittent operate 0 hour before/after close Weekdays: on at 5 pm, off at 7 am Weekend: on at 4 pm, off at 9 am No baseboard No economizer	Thermostat setpoint Unoccupied/occupied Heating 60°F/68°F Cooling 85°F/78°F ENERGY STAR Air source heat pump >= 8.2 HSPF/ >=14.5 SEER/ >=12 EER* for split systems >= 8.0 HSPF/ >=14 SEER/ >=11 EER* for single package equipment including gas/electric package units Central air system >=14.5 SEER/ >=12 EER* for split systems >=14 SEER/ >=11 EER* for single package equipment including gas/electric package units Furnace (natural gas) AFUE 0.90
Domestic water heating	Heater fuel: natural gas Heater type: storage Hot water use: 16.45 gal/person/day Input rating: 19.3 (38.6) kBtuh Energy factor 0.67 Storage tank: capacity 21(42) gallons Insulation R value: 12 h ft^2 °F/Btu Water temperature: supply 110°F equal ground temperature Pumping recirculation: 0%	ASHRAE 90.2-2007 Hot water consumption 16.45 gal/person/day (With a cloth washer, and a spa tub in the unit) ENERGY STAR Gas Storage EF >= 0.67

Table 45. Commercial building ASHRAE compliant model inputs in eQUEST.

<table>
<tr><th>Item</th><th colspan="3">Details</th><th>References</th></tr>
<tr><td>Project type</td><td colspan="3">Office Bldg.</td><td></td></tr>
<tr><td>Location</td><td colspan="3">User selected: 16 cities</td><td></td></tr>
<tr><td>Analysis year</td><td colspan="3">2010</td><td></td></tr>
<tr><td rowspan="2">Dimension</td><td>Small
60 ft x 90 ft
1 story
5,400 ft^2
Pitched roof
20° tilted</td><td>Medium
110 ft x 162.5 ft
3 stories
53,630 ft^2
Flat roof</td><td>Big
154 ft x 320 ft
12 stories
+ 1 basement
460,240 ft^2
Flat roof</td><td rowspan="2">DOE Commercial reference buildings (based on 2006 EIA survey)</td></tr>
<tr><td colspan="3">Aspect ratio 1.5
Perimeter zone dept. 15 ft
Floor to floor: 13.0 ft
Floor to ceiling: 9.0 ft</td></tr>
<tr><td>Orientation</td><td colspan="3">The building energy consumption is an average of the same building facing north, east, south and west orientation (0,90,180,270 degree from north)</td><td>ASHRAE 90.1-2007 Appendix G</td></tr>
<tr><td>Roof</td><td colspan="3">Construction layers
• Metal frame, > 24 in o.c.
• Roof, built-up
• 1 in polystyrene
o Miami-
o Houston, Phoenix, Atlanta, Los Angeles, Las Vegas, San Francisco, Baltimore, Albuquerque, Seattle, Chicago, Denver, Minneapolis, Helena, Duluth, Fairbanks R-4
• Insulation
o Miami R-13 (U=0.061)
o Houston, Phoenix, Atlanta, Los Angeles, Las Vegas, San Francisco, Baltimore, Albuquerque, Seattle, Chicago, Denver, Minneapolis, Helena, Duluth, Fairbanks R-15 (U=0.045)
Absorptance 0.7 (Red oil)</td><td>ASHRAE 90.1-2007
Insulation entirely above deck

U
Miami = 0.063
Houston, Phoenix, Atlanta, Los Angeles, Las Vegas, San Francisco, Baltimore, Albuquerque, Seattle, Chicago, Denver, Minneapolis, Helena, Duluth, Fairbanks = 0.048

Reflectance 0.3</td></tr>
<tr><td>Wall</td><td colspan="3">Construction layers
• Metal frame 2x6, 24 in o.c.
• Wood/plywood
• 1 ½ in fiber board
o Miami, Houston, Phoenix R-6,
o Atlanta, Los Angeles, Las Vegas, San Francisco R-9
o Baltimore, Albuquerque, Seattle, Chicago, Denver, Minneapolis, Helena, Duluth, Fairbanks R-6
• Insulation</td><td>ASHRAE 90.1-2007

U Steel frame
Miami, Houston, Phoenix = 0.124
Atlanta, Los Angeles, Las Vegas, San Francisco = 0.084
Baltimore, Albuquerque, Seattle, Chicago, Denver,</td></tr>
</table>

Item	Details	References
	o Miami, Houston, Phoenix (U=0.110) o Atlanta, Los Angeles, Las Vegas, San Francisco (U=0.084) o Baltimore, Albuquerque, Seattle, Chicago, Denver, Minneapolis, Helena, Duluth, Fairbanks R-11 (U=0.064) • Gypsum board ½ in Absorptance 0.5 (Green light)	Minneapolis, Helena, Duluth, Fairbanks = 0.064
Below-grade wall	Construction layers (for big commercial buildings only) • 6 in concrete • Insulation o Miami, Houston, Phoenix, Atlanta, Los Angeles, Las Vegas, San Francisco, Baltimore, Albuquerque, Seattle (C=0.216), o Chicago, Denver, Minneapolis, Helena, Duluth, Fairbanks R-10 8 ft deep (C=0.087)	ASHRAE 90.1-2007 C Miami, Houston, Phoenix, Atlanta, Los Angeles, Las Vegas, San Francisco, Baltimore, Albuquerque, Seattle = 1.140 Chicago, Denver, Minneapolis, Helena, Duluth, Fairbanks = 0.119
Floor	Construction layers • Metal frame 2x6, 24 in o.c. • Wood/Plywood • Polystyrene o Miami 1 in (U = 0.236) o Houston, Phoenix, Atlanta, Los Angeles, Las Vegas, San Francisco 4 in (R-5/in) (U = 0.044), o Baltimore, Albuquerque, Seattle, Chicago, Denver, Minneapolis, Helena, Duluth 5 in (R-5/in) (U = 0.035), o Fairbanks 6 in (R-5/in) (U = 0.030)	ASHRAE 90.1-2007 Steel-joist U Miami = 0.35 Houston, Phoenix, Atlanta, Los Angeles, Las Vegas, San Francisco = 0.052 Baltimore, Albuquerque, Seattle, Chicago, Denver, Minneapolis, Helena, Duluth = 0.038 Fairbanks = 0.032
Infiltration	Perim: 0.038 CFM/ft^2 (ext. wall area) Core: 0.001 CFM/ft^2 (floor area)	eQUEST default
Interior: ceilings	Lay-in acoustic tile No insulation	eQUEST default
Interior: vertical walls	Frame No insulation	eQUEST default
Interior: floor	Carpet (no pad) 4 in concrete	eQUEST default
Door	1 each orientation 7 ft x 6 ft Air lock entry Miami, Houston, Phoenix, Atlanta, Los Angeles, Las Vegas, San Francisco, Baltimore, Albuquerque, Seattle	ASHRAE 90.1 U Miami, Houston, Phoenix, Atlanta, Los Angeles, Las Vegas,

Item	Details	References
	Single PPG Starphire 6 mm (Code 5501): U= 1.03, SHGC = 0.9, VT = 0.91 Chicago, Denver, Minneapolis, Helena, Duluth, Fairbanks Double PPG Starphire/Air/Clear 6mm (Code6501): U=0.47, SHGC=0.78, VT=0.81 Aluminum without brk 3.0 in.	San Francisco, Baltimore, Albuquerque, Seattle = 1.45 Chicago, Denver, Minneapolis, Helena, Duluth, Fairbanks = 0.5
Exterior window	Miami, Houston, Phoenix Atlanta, Los Angeles, Las Vegas, San Francisco Double guardian Sun-guard LE40/Air/Clear 6mm (Code 6459): U=0.33, SHGC = 0.24, VT = 0.34 Baltimore, Albuquerque, Seattle, Chicago, Denver, Minneapolis, Helena Double guardian Perf Plus II Clear/Thin Air/Clear 6mm (Code 6471): U=0.4, SHGC = 0.4, VT = 0.67 Duluth, Fairbanks Double AFG Ti-R LowE/ThinAir/Clear 6 mm (Code 6189): U=0.40, SHGC = 0.44, VT = 0.66 Frame: aluminum, operable 1.30 in Window height 5.22 ft, sill 3.00 ft 40% each direction No overhang, no fin No interior shading	ASHRAE 90.1 U Miami, = 1.20 Houston, Phoenix = 0.75 Atlanta, Los Angeles, Las Vegas, San Francisco = 0.65 Baltimore, Albuquerque, Seattle, Chicago, Denver, Minneapolis, Helena = 0.55 Duluth, Fairbanks = 0.45 SHGC Miami, Houston, Phoenix, Atlanta, Los Angeles, Las Vegas, San Francisco = 0.25 Baltimore, Albuquerque, Seattle, Chicago, Denver, Minneapolis, Helena = 0.40 Duluth, Fairbanks = 0.45
Building operation schedule	Typical use Weekdays 8 am-5 pm Weekend closed	eQUEST default
Activity areas allocation	**Space % sf/per CFM/per** Open office 40 200 17 Private office 30 200 17 Corridor 10 1,000 50 Lobby 5 100 7 Restroom 5 300 50 Conference 4 20 5 M&E 4 2,000 100 Copy room 2 200 100	ASHRAE 60.1-2010
Zone group	6 zones: 3 floors, each with core and perimeter zones	eQUEST default
Ambient lighting/ task lighting/ office	**Space L misc.** Open office 1.1 2.2	ASHRAE 90.1-2007

Item	Details	References
equipment/ misc.	Private office 1.1 2.2 Corridor 0.5 0.00 Lobby 1.3 1.0 Restroom 0.9 0.10 Conference 1.3 0.10 M&E 1.5 0.10 Copy room 1.5 0.70	
Exterior lighting	1.0 W/ft^2	
Domestic hot water	Model DHW equipment with seasonal profile	eQUEST default
HVAC System 1	**Small office** Cooling source: DX coils Heating source: furnace System type: packaged multizone with furnace 1 system/zone Return air: ducted Thermostat setpoint Occupied cool: 76°F, heat 70°F Unoccupied cool: 82°F, heat 64°F Design temperature Cooling: indoor 75°F, supply 55°F Heating: indoor 72°F, supply 92°F Air flow: min design flow 0.5 CFM/ft^2 VAV minimum flow: Core 100%, perimeter 100% Cooling: Auto-size 135-240 kBtuh or 11.25-20 tons EER = 11 Allow crankcase heating Heating: Auto-size >= 225 kBtuh Efficiency 0.80 Supply fan: power 1.25 in. WG High efficiency Auto-size flow (with 1.15 safety factor) Fan schedule: no fan night cycle 1 hour before/after close Weekdays: on at 7 am, off at 6 pm Weekend: off No baseboard Economizer: dry bulb temp high limit shut off Miami Houston Phoenix, Atlanta, Baltimore – no economizer Los Angeles, Las Vegas, San Francisco, Albuquerque, Seattle, Denver, Helena, Fairbanks 75°F Chicago, Minneapolis, Duluth 70°F	ASHRAE 90.1-2007 Small office Package rooftop AC • Constant fan • Direct expansion cooling • Fossil fuel furnace Medium office Package rooftop VAV with reheat • VAV fan • Direct expansion cooling • Hot-water fossil fuel boiler Big office Package rooftop VAV with reheat • VAV fan • Chilled water cooling • Hot-water fossil fuel boiler Supply-air-to-room-air temperature Δ = 20°F Economizer Required at all locations except Miami, Houston, Atlanta, Baltimore Economized high limit shut off: Los Angeles, Las Vegas, San Francisco, Albuquerque, Seattle, Denver, Helena,

Item	Details	References
	Medium office Cooling source: DX Coils Heating source: hot water coils Hot water source: hot water loop System type: package VAV with HW reheat 1 system/floor Return air: ducted Thermostat setpoint Occupied cool: 76°F, heat 70°F Unoccupied cool: 82°F, heat 64°F Design temperature Cooling: indoor 75°F, supply 55°F Heating: indoor 72°F, supply 92°F Air flow: min design flow 0.5 CFM/ft^2 VAV minimum flow: Core 40% perimeter 30% Cooling: auto-size 135-240 kBtuh or 11.25-20 tons EER = 11 Allow crankcase heating Supply fan: power 2.00 in. WG High efficiency Auto-size flow (with 1.15 safety factor) Variable speed drive Fan schedule: no fan night cycle 1 hour before/after close Weekdays: on at 7 am, off at 6 pm Weekend: off No baseboard Heat/reheat hot water: 30Δ°F Economizer: dry bulb temp high limit shut off Miami Houston Phoenix, Atlanta, Baltimore – no economizer Los Angeles, Las Vegas, San Francisco, Albuquerque, Seattle, Denver, Helena, Fairbanks 75°F Chicago, Minneapolis, Duluth 70°F Cold deck reset: outside air reset Outside hi/lo 80°F/60°F Supply min/max 44°F/54°F **Big office** Cooling source: chill water coil Heating source: hot water coil Hot water source: hot water loop System type: standard VAV with HW reheat	Fairbanks 75°F Chicago, Minneapolis, Duluth 70°F System efficiency ASHRAE 90.1 table 6.8.1A-6.8.1C Chill water supply temperature reset 44°F at 80°F and above 54°F at 60°F and below Exhaust air energy recovery 50% except Heating: Miami Houston Phoenix, Atlanta, Baltimore Los Angeles, Las Vegas, San Francisco Cooling: San Francisco, Seattle, Denver, Helena, Duluth, Fairbanks VAV minimum flow setpoint For medium and big office buildings, it is 0.4 cfm/ft^2, or minimum ventilation rate, whichever is larger.

Item	Details	References
	1 system/floor Return air: ducted Thermostat setpoint Occupied cool: 76°F, heat 70°F Unoccupied cool: 82°F, heat 64°F Design temperature Cooling: indoor 75°F, supply 55°F Heating: indoor 72°F, supply 92°F Air flow: min design flow 0.5 CFM/ft^2 VAV minimum flow: Core 40% perimeter 30% Supply fan: power 3.50 in. WG High efficiency Auto-size flow (with 1.15 safety factor) Variable speed drive Return fan: power 1.17 in. WG High efficiency Auto-size flow Variable speed drive Fan schedule: no fan night cycle 1 hour before/after close Weekdays: on at 7 am, off at 6 pm Weekend: off No baseboard Heat/reheat hot water: 30Δ°F Economizer: dry bulb temp high limit shut off Miami Houston Phoenix, Atlanta, Baltimore – no economizer Los Angeles, Las Vegas, San Francisco, Albuquerque, Seattle, Denver, Helena, Fairbanks 75°F Chicago, Minneapolis, Duluth 70°F Cold deck reset: outside air reset Outside hi/lo 80°F/60°F Supply min/max 44°F/54°F	
Cooling primary equipment	**Big office** Chilled water system CHW loop: head 56.6 ft Design DT 10°F Pump: single system pump only No. of system pump: 2 CHW loop flow: variable Pump control: VSD Motor efficiency: high Estimated CHW load: 460,205 ft^2 x size factor 1.15/480ft^2/ton = 1102.6 tons Chiller	ASHRAE 90.1-2007 Type and number of chillers ≤300 tons = 1 water-cooled screw chiller >300 tons, <600 tons = 2 water-cooled screw chillers sized equally. ≥600 tons = 2 water-cooled centrifugal chillers minimum with chillers added so that no chiller is larger than

Item	Details	References
	Type: electric centrifugal hermetic Condenser type: water-cooled 2 auto-sized >300 tons Efficiency: COP 6.1 Water cooled condenser/cooling tower Condenser water loop head: 61.6 ft Design DT 10°F Configuration: open tower Temp control: reset min T @ 70°F Capacity control: two speed fan Fan efficiency: high Fan type: centrifugal Schedule: setpoint reset CHW min T = 44°F, CHW max T = 54°F Operation: stand by On at 7 am, off at 6 pm	800 tons, all sized equally Chilled-water pump power 22W/gpm Primary/secondary system ≥300 tons, VSD on the second loop <300 tons, riding the pump curve on the second loop Heat rejection An axial fan cooling tower with two speed fans, supply temperature 85°F or 10°F approaching design supply temperature, maintain 70°F leaving water temperature, pump power is 19W/gpm Cooling equipment capacity must be oversized by 15%
Heating primary equipment	**Medium office and big office** Hot water system HW loop: head 36.6 ft Design DT 40°F Pump: single system pump only No. of system pump: 1 HW loop flow: constant Motor efficiency: high Boiler Type: HW boiler (natural draft) Fuel: natural gas No: 1 autosized 300-2,500 kBtu (1 or 2 auto-sized > 2,500 kBtuh Efficiency: 80% Schedule: setpoint fixed at 180°F Operation: stand by On at 7 am, off at 6 pm	ASHRAE 90.1-2007 Two equal-size boilers for buildings > 150,000 ft^2 Hot water supply boiler, gas & oil Thermal efficiency = 80% Hot water • Supply T 180°F • Return T 130°F Hot water supply temperature reset • 180F at 20°F and below • 150F at 50°F and above Hot water pump power:

Item	Details	References
		19 w/gpm Pumps should be modeled as Primary-only with continuous variable flow, riding the pump curve Big office – pumps modeled with VSD Heat equipment capacity must be oversized by 25%
Non-residential Domestic water heating	Heater fuel: Natural gas Heater type: Storage Hot water use: 1 gallon/person/day **Small office** Input rating: 18.7 kBtuh Efficiency: 0.80 Storage tank: capacity 14 gallons Insulation R value: 12 h ft^2 °F/Btu Stand by loss 2.04%/hr Water temperature: supply 135°F equal ground temperature Pumping recirculation: 0% **Medium office** Input rating: 228.9 kBtuh Efficiency: 0.80 Storage tank: capacity 172 gallons Insulation R value: 12 h ft^2 °F/Btu Stand by loss: 1.85 %/hr Water temperature: supply 135°F equal ground temperature Pumping recirculation: 0% **Big office** Input rating: 1,965.3 kBtuh Efficiency: 0.80 storage tank: capacity 1,475 gallons Insulation R value: 12 h ft^2 °F/Btu Stand by loss 2.04%/hr Water temperature: supply 135°F equal ground temperature Pumping recirculation: 0%	ASHRAE 90.1 Table 7.8

Table 46. Industrial building ASHRAE compliant model inputs in eQUEST.

Item	Details	References
Project type	Manufacturer	
Location	User selected: 16 cities	
Analysis year	2010	
Dimension	387.3 ft x 258.2 ft 1 story 100,000 ft^2 Aspect ratio 1.5 Perimeter zone dept 15 ft Floor to floor: 35 ft Floor to ceiling: 35 ft	DOE Commercial reference buildings (based on 2006 EIA survey)
Orientation	The building energy consumption is an average of the same building facing north, east, south, and west orientation (0,90,180,270 degree from north)	ASHRAE 90.1-2007 Appendix G
Roof	Construction layers • Metal frame, > 24 in. o.c. • Roof, built-up • 1 in polystyrene o Miami- o Houston, Phoenix, Atlanta, Los Angeles, Las Vegas, San Francisco, Baltimore, Albuquerque, Seattle, Chicago, Denver, Minneapolis, Helena, Duluth, Fairbanks R-4 • Insulation o Miami R-13 (U=0.061) o Houston, Phoenix, Atlanta, Los Angeles, Las Vegas, San Francisco, Baltimore, Albuquerque, Seattle, Chicago, Denver, Minneapolis, Helena, Duluth, Fairbanks R-15 (U=0.045) Absorptance 0.7 (Red oil)	ASHRAE 90.1-2007 Insulation entirely above deck U Miami = 0.063 Houston, Phoenix, Atlanta, Los Angeles, Las Vegas, San Francisco, Baltimore, Albuquerque, Seattle, Chicago, Denver, Minneapolis, Helena, Duluth, Fairbanks = 0.048 Reflectance 0.3
Wall	Construction layers • Metal frame 2x6, 24 in o.c. • Wood/plywood • 1 ½ in fiber board o Miami, Houston, Phoenix R-6 o Atlanta, Los Angeles, Las Vegas, San Francisco R-9 o Baltimore, Albuquerque, Seattle, Chicago, Denver, Minneapolis, Helena, Duluth, Fairbanks R-6 • Insulation o Miami, Houston, Phoenix (U=0.110) o Atlanta, Los Angeles, Las Vegas, San Francisco – (U=0.084)	ASHRAE 90.1-2007 Steel frame U Miami, Houston, Phoenix = 0.124 Atlanta, Los Angeles, Las Vegas, San Francisco = 0.084 Baltimore, Albuquerque, Seattle, Chicago, Denver, Minneapolis, Helena, Duluth, Fairbanks =

Item	Details	References
	o Baltimore, Albuquerque, Seattle, Chicago, Denver, Minneapolis, Helena, Duluth, Fairbanks R-11 (U=0.064) • Gypsum board ½ in Absorptance 0.5 (Green light)	0.064
Floor	Construction layers • Metal frame 2x6, 24 in o.c. • Wood/plywood • Polystyrene o Miami ½ in (U = 0.236) o Houston, Phoenix, Atlanta, Los Angeles, Las Vegas, San Francisco 4 in (R-5/in) (U = 0.044), o Baltimore, Albuquerque, Seattle, Chicago, Denver, Minneapolis, Helena, Duluth 5 in (R-5/in) (U = 0.035) o Fairbanks 6 in (R-5/in) (U = 0.030)	ASHRAE 90.1-2007 Steel-joist U Miami = 0.35 Houston, Phoenix, Atlanta, Los Angeles, Las Vegas, San Francisco = 0.052 Baltimore, Albuquerque, Seattle, Chicago, Denver, Minneapolis, Helena, Duluth = 0.038 Fairbanks = 0.032
Infiltration	Perim: 0.038 C FM/ft^2 (ext. wall area) Core: 0.001 CFM/ft^2 (floor area)	eQUEST default
Interior: ceilings	Lay-in acoustic tile No insulation	eQUEST default
Interior: vertical walls	Frame No insulation	eQUEST default
Interior: floor	Carpet (no pad) 4 in concrete	eQUEST default
Door	1 each orientation 7 ft x 6 ft Air lock entry Miami, Houston, Phoenix, Atlanta, Los Angeles, Las Vegas, San Francisco, Baltimore, Albuquerque, Seattle Single PPG Starphire 6 mm (Code 5501): U = 1.03, SHGC = 0.9, VT = 0.91 Chicago, Denver, Minneapolis, Helena, Duluth, Fairbanks Double PPG Starphire/Air/Clear 6mm (Code 6501): U = 0.47, SHGC = 0.78, VT = 0.81 Aluminum without brk 3.0 in.	ASHRAE 90.1 U Miami, Houston, Phoenix, Atlanta, Los Angeles, Las Vegas, San Francisco, Baltimore, Albuquerque, Seattle = 1.45 Chicago, Denver, Minneapolis, Helena, Duluth, Fairbanks = 0.5
Exterior window	Miami, Houston, Phoenix Atlanta, Los Angeles, Las Vegas, San Francisco Double guardian Sun-guard LE40/Air/Clear 6mm (Code 6459): U=0.33, SHGC = 0.24, VT = 0.34	ASHRAE 90.1 U Miami, = 1.20 Houston, Phoenix = 0.75 Atlanta, Los Angeles,

Item	Details	References
	Baltimore, Albuquerque, Seattle, Chicago, Denver, Minneapolis, Helena Double guardian Perf Plus II Clear/Thin Air/Clear 6mm (Code 6471): U = 0.4, SHGC = 0.4, VT = 0.67 Duluth, Fairbanks Double AFG Ti-R LowE/ThinAir/Clear 6 mm (Code 6189): U = 0.40, SHGC = 0.44, VT = 0.66 Frame: aluminum, operable 1.30 in Window height 5.22 ft sill 3.00 ft 40% each direction No overhang, no fin No interior shading	Las Vegas, San Francisco = 0.65 Baltimore, Albuquerque, Seattle, Chicago, Denver, Minneapolis, Helena = 0.55 Duluth, Fairbanks = 0.45 SHGC Miami, Houston, Phoenix, Atlanta, Los Angeles, Las Vegas, San Francisco = 0.25 Baltimore, Albuquerque, Seattle, Chicago, Denver, Minneapolis, Helena = 0.40 Duluth, Fairbanks = 0.45
Building operation schedule	Typical use Weekdays 9 am-5 pm Weekend closed	eQUEST default
Activity areas allocation	Space / % / sf/per / CFM/per / Li W/sf / misc. Comm/Ind work / 60 / 300 / 15 / 1.7 / 1.0 Storage / 30 / 500 / 75 / 0.9 / 0 Office / 10 / 200 / 20 / 1.1 / 0.75 Restroom / 5 / 300 / 50 / 0.9 / 0.1 M&E / 4 / 2,000 / 100 / 1.2 / 0.1	eQUEST default
Zone group	2 zones: 1 floors, each with core and perimeter zones	eQUEST default
Exterior lighting	1.25 W/ft^2	ASHRAE 90.1-2007 Table 9.4.5
Domestic hot water	Model DHW Equipment with seasonal profile	eQUEST default
HVAC System 1	Cooling source: DX Coils Heating source: hot water coils Hot water source: hot water loop System type: package VAV with HW reheat 1 system/floor Return air: ducted Thermostat setpoint Occupied cool: 76°F, heat 70°F Unoccupied cool: 82°F, heat 64°F Design temperature Cooling: indoor 75°F, supply 55°F Heating: indoor 72°F, supply 92°F Air flow: min design flow 0.5 CFM/ft^2 VAV minimum flow: Core 40% perimeter 30% Cooling: Auto-size 135-240 kBtuh or 11.25-20 tons EER = 11	ASHRAE 90.1-2007 • Package rooftop VAV with reheat • VAV fan • Direct expansion cooling • Hot-water fossil fuel boiler Supply-air-to-room-air temperature Δ = 20°F Economizer Required at all locations except Miami, Houston, Atlanta, Baltimore Economized high limit

Item	Details	References
	Allow crankcase heating Supply fan: power 2.00 in. WG High efficiency Auto-size flow (with 1.15 safety factor) Variable speed drive Fan schedule: no fan night cycle 1 hour before/after close Weekdays: on at 8 am, off at 6 pm Weekend: off No baseboard Heat/reheat hot water: 30Δ°F Economizer: dry bulb temp high limit shut off Miami Houston Phoenix, Atlanta, Baltimore – no economizer Los Angeles, Las Vegas, San Francisco, Albuquerque, Seattle, Denver, Helena, Fairbanks 75°F Chicago, Minneapolis, Duluth 70°F Cold deck reset: outside air reset Outside hi/lo 80°F 60°F Supply min/max 44°F 54°F	shut off: Los Angeles, Las Vegas, San Francisco, Albuquerque, Seattle, Denver, Helena, Fairbanks 75°F Chicago, Minneapolis, Duluth 70°F System efficiency ASHRAE 90.1 table 6.8.1A-6.8.1C Chill water supply temperature reset 44°F at 80°F and above 54°F at 60°F and below Exhaust air energy recovery 50% except Heating: Miami Houston Phoenix, Atlanta, Baltimore Los Angeles, Las Vegas, San Francisco Cooling: San Francisco, Seattle, Denver, Helena, Duluth and Fairbanks VAV minimum flow setpoint 0.4 cfm/ft^2 or minimum ventilation rate, whichever is larger.
Heating primary equipment	Hot water system HW loop: head 36.6 ft Design DT 40°F Pump: single system pump only No. of system pump: 1 HW loop flow: constant Motor efficiency: high Boiler Type: HW boiler (natural draft) Fuel: natural gas No: 1 autosized 300-2,500 kBtu Efficiency: 80**%** Schedule: setpoint fixed at 180°F Operation: stand by	ASHRAE 90.1-2007 Hot water supply boiler, gas & oil thermal efficiency = 80% Hot water • Supply T 180°F • Return T 130°F Hot water supply temperature reset • 180F at 20°F and below • 150F at 50°F and

Item	Details	References
	On at 8 am, off at 6 pm	above Hot water pump power: 19 w/gpm Pumps should be modeled as primary-only with continuous variable flow, riding the pump curve Heat equipment capacity must be oversized by 25%
Non-residential domestic water heating	Heater fuel: natural gas Heater type: storage Hot water use: 1 gallon/person/day Input rating: 207.3 kBtuh Efficiency: 0.80 Storage tank: capacity 156 gallons Insulation R value: 12 h ft^2 °F/Btu Stand by loss: 1.91 %/hr Water temperature: supply 135°F equal ground temperature Pumping recirculation: 0%	ASHRAE 90.1 Table 7.8

APPENDIX B

ENERGY EFFICIENCY DESIGN STRATEGIES AND GRID-CONNECTED PV SYSTEMS PERFORMANCE TABLES IN SMALL HOUSES, MEDIUM OFFICE BUILDINGS AND FACTORY BUILDINGS IN SIX CITIES

Table 47. Performances of energy efficiency design strategies and grid-connected PV systems implemented in small houses in Miami.

Metrices	Existing	ASHRAE	Wall insulation	Roof insulation	Glazing	Wall, roof, glazing	Daylighting	Thermal Mass	Cooling	Heating	Lighting power density	High efficiency appliance	Thermostat	Passive house	Zero energy building
Electricity consumption															
Annual electricity consumption (kWh)	11,847	5,806	5,583	5,774	5,735	5,450	5,784	5,972	5,603	5,806	5,200	5,351	5,241	4,505	4,143
Annual electricity consumption with typical size grid-connected PV systems	-	936	714	905	865	581	915	1,103	733	936	331	482	371	(365)	(727)
% Annual electricity reduction compared with ZEBs	-	9%	21%	11%	13%	29%	10%	0%	20%	9%	42%	34%	40%	80%	100%
Peak load (kW)	5.4	3.1	2.7	3.1	3.0	2.6	3.0	3.0	2.9	3.1	2.9	3.0	3.0	2.3	2.2
Peak load with PV systems installed	-	2.9	2.5	2.9	2.9	2.4	2.9	2.8	2.7	2.9	2.7	2.8	2.9	2.1	2.0
% Peak load reduction compared with ZEBs	-	0%	50%	0%	4%	54%	2%	9%	22%	0%	25%	13%	1%	90%	100%
Excess PV output and building power load met															
Electricity bought from grid (kWh)	10,469	4,566	4,347	4,534	4,495	4,215	4,547	4,734	4,363	4,566	3,975	4,235	4,003	3,407	3,046
Load met by PV output (kWh)	-	1,240	1,237	1,240	1,239	1,235	1,237	1,238	1,240	1,240	1,226	1,116	1,237	1,097	1,097
% Load met compared to total demand	0%	21%	22%	21%	22%	23%	21%	21%	22%	21%	24%	21%	24%	24%	26%
% Percentage load met by PV output compared with ZEBs	-	11%	25%	13%	15%	34%	11%	0%	24%	11%	49%	2%	50%	63%	100%
Excess electricity sold to grid (kWh)	-	3,629	3,632	3,629	3,630	3,634	3,632	3,631	3,629	3,629	3,643	3,753	3,632	3,772	3,773
% Excess electricity reduction compared with ZEBs	-	100%	97%	100%	99%	97%	98%	98%	100%	100%	90%	14%	98%	1%	0%
Economic analysis															
Annual electricity cost (Normal rate)	-	$ -	$ 82	$ 104	$ 99	$ 67	$ 105	$ 126	$ 84	$ 107	$ 38	$ 55	$ 43	$ (42)	$ (83)
Annual gas cost	-	$ -	$ 87	$ 113	$ 114	$ 89	$ 112	$ 105	$ 112	$ 108	$ 113	$ 113	$ 98	$ 19	$ 12
Total annual energy cost	-	$ -	$ 169	$ 216	$ 213	$ 156	$ 217	$ 231	$ 196	$ 216	$ 151	$ 168	$ 141	$ (23)	$ (71)
% Energy cost saving (Normal rate)	-	-	78%	72%	73%	80%	72%	70%	75%	72%	81%	78%	82%	103%	109%
$ Incremental investment from ASHRAE compliant building	-	-	$ 36,563	$ 33,524	$ 39,747	$ 45,834	$ 33,549	$ 35,615	$ 32,414	$ 32,600	$ 32,029	$ 33,680	$ 32,000	$ 51,033	$ 48,557
% Investment cost reduction compared with the highest invesment strategy	-	-	76%	92%	59%	27%	92%	81%	98%	97%	100%	91%	100%	0%	13%
Payback period (Year)	-	-	60	60	70	74	60	65	56	58	51	55	50	64	57
% Payback period reductioncompared with the longest payback period strategy	-	-	58%	60%	14%	0%	59%	36%	77%	67%	96%	79%	100%	42%	70%
Emission															
Site emission (Ton CO2e)	-	0.83	0.63	0.80	0.77	0.53	0.81	0.94	0.67	0.82	0.37	0.48	0.38	(0.26)	(0.54)
% Site emission (Ton CO2e) reduction compared with ZEBs	-	8%	21%	10%	12%	28%	9%	0%	18%	8%	39%	31%	38%	81%	100%
Source emission (Ton CO2e)	-	2.52	1.92	2.44	2.34	1.58	2.46	2.93	2.00	2.51	0.97	1.36	1.06	(0.91)	(1.84)
% Reduction compared with existing buildings	-	72%	79%	73%	74%	83%	73%	68%	78%	72%	89%	85%	88%	110%	120%

Table 48. Performances of energy efficiency design strategies and grid-connected PV systems implemented in small houses in Phoenix.

Metrices	Existing	ASHRAE	Wall insulation	Roof insulation	Glazing	Wall, roof, glazing	Daylighting	Thermal Mass	Cooling	Heating	Lighting power density	High efficiency appliance	Thermostat	Passive house	Zero energy building
Electricity consumption															
Annual electricity consumption (kWh)	12,701	6,589	6,201	6,556	6,487	6,050	6,562	6,636	6,328	6,589	6,003	6,151	6,242	5,194	4,976
Annual electricity consumption with typical size grid-connected PV systems	-	668	280	635	566	129	641	715	407	668	82	231	321	(727)	(945)
% Annual electricity reduction compared with ZEBs	-	3%	26%	5%	9%	35%	4%	0%	19%	3%	38%	29%	24%	87%	100%
Peak load (kW)	8.1	4.0	3.4	4.0	3.8	3.3	3.9	3.9	3.7	4.0	3.7	3.9	4.0	3.0	3.1
Peak load with PV systems installed	-	3.7	3.2	3.7	3.6	3.0	3.7	3.6	3.4	3.7	3.5	3.6	3.7	2.7	2.9
% Peak load reduction compared with ZEBs	-	0%	55%	0%	13%	68%	1%	9%	28%	0%	23%	8%	0%	100%	85%
Excess PV output and building power load met															
Electricity bought from grid (kWh)	11,163	5,195	4,815	5,161	5,096	4,667	5,172	5,251	4,936	5,195	4,625	4,884	4,856	3,947	3,730
Load met by PV output (kWh)	-	1,394	1,386	1,395	1,390	1,383	1,390	1,386	1,392	1,394	1,378	1,267	1,386	1,246	1,246
% Load met compared to total demand	0%	21%	22%	21%	21%	23%	21%	21%	22%	21%	23%	21%	22%	24%	25%
% Percentage load met by PV output compared with ZEBs	-	12%	39%	15%	19%	51%	13%	6%	32%	12%	53%	0%	36%	76%	100%
Excess electricity sold to grid (kWh)	-	4,527	4,535	4,526	4,530	4,538	4,530	4,535	4,528	4,527	4,542	4,654	4,535	4,674	4,674
% Excess electricity reduction compared with ZEBs	-	99%	94%	100%	97%	92%	97%	94%	98%	99%	89%	14%	94%	0%	0%
Economic analysis															
Annual electricity cost (Normal rate)	-	$ -	$ 32	$ 73	$ 65	$ 15	$ 74	$ 82	$ 47	$ 77	$ 9	$ 26	$ 37	$ (83)	$ (108)
Annual gas cost	-	$ -	$ 219	$ 277	$ 286	$ 224	$ 278	$ 265	$ 278	$ 261	$ 285	$ 282	$ 236	$ 126	$ 95
Total annual energy cost	-	$ -	$ 251	$ 350	$ 351	$ 239	$ 351	$ 347	$ 325	$ 338	$ 294	$ 309	$ 273	$ 43	$ (13)
% Energy cost saving (Normal rate)	-	-	76%	66%	66%	77%	66%	66%	69%	67%	72%	70%	74%	96%	101%
$ Incremental investment from ASHRAE compliant building	-	-	$ 36,183	$ 33,524	$ 39,747	$ 45,454	$ 33,549	$ 35,615	$ 32,460	$ 32,550	$ 32,029	$ 33,680	$ 32,000	$ 50,653	$ 48,173
% Investment cost reduction compared with the highest invesment strategy	-	-	78%	92%	58%	28%	92%	81%	98%	97%	100%	91%	100%	0%	13%
Payback period (Year)	-	-	46	49	58	57	49	52	46	47	43	46	42	51	46
% Payback period reductioncompared with the longest payback period strategy	-	-	74%	57%	0%	6%	56%	39%	77%	71%	92%	73%	100%	44%	75%
Emission															
Site emission (Ton CO2e)	-	0.80	0.44	0.77	0.73	0.33	0.78	0.82	0.60	0.78	0.36	0.47	0.49	(0.42)	(0.62)
% Site emission (Ton CO2e) reduction compared with ZEBs	-	2%	26%	3%	6%	34%	3%	0%	15%	3%	32%	24%	23%	86%	100%
Source emission (Ton CO2e)	-	2.02	0.96	1.94	1.77	0.58	1.95	2.13	1.36	2.00	0.53	0.91	1.09	(1.71)	(2.30)
% Reduction compared with existing buildings	-	80%	90%	81%	82%	94%	81%	79%	87%	80%	95%	91%	89%	117%	123%

Table 49. Performances of energy efficiency design strategies and grid-connected PV systems implemented in small houses in Las Vegas.

Metrices	Existing	ASHRAE	Wall insulation	Roof insulation	Glazing	Wall, roof, glazing	Daylighting	Thermal Mass	Cooling	Heating	Lighting power density	High efficiency appliance	Thermostat	Passive house	Zero energy building
Electricity consumption															
Annual electricity consumption (kWh)	10,570	6,031	5,757	6,008	5,906	5,608	5,949	6,106	5,845	6,031	5,468	5,600	5,762	4,768	4,555
Annual electricity consumption with typical size grid-connected PV systems	-	(18)	(293)	(42)	(143)	(442)	(101)	56	(204)	(18)	(581)	(450)	(287)	(1,282)	(1,494)
% Annual electricity reduction compared with ZEBs	-	5%	23%	6%	13%	32%	10%	0%	17%	5%	41%	33%	22%	86%	100%
Peak load (kW)	7.1	3.6	3.1	3.6	3.5	3.0	3.5	3.6	3.4	3.6	3.5	3.5	3.6	2.7	2.8
Peak load with PV systems installed	-	3.4	2.9	3.4	3.3	2.9	3.4	3.4	3.2	3.4	3.2	3.3	3.4	2.5	2.6
% Peak load reduction compared with ZEBs	-	0%	56%	0%	9%	63%	1%	6%	27%	0%	23%	15%	0%	100%	93%
Excess PV output and building power load met															
Electricity bought from grid (kWh)	9,059	4,680	4,408	4,656	4,558	4,262	4,614	4,757	4,494	4,680	4,142	4,382	4,415	3,584	3,375
Load met by PV output (kWh)	-	1,352	1,349	1,352	1,349	1,346	1,334	1,349	1,351	1,352	1,327	1,218	1,347	1,184	1,180
% Load met compared to total demand	0%	22%	23%	23%	23%	24%	22%	22%	23%	22%	24%	22%	23%	25%	26%
% Percentage load met by PV output compared with ZEBs	-	16%	41%	18%	26%	54%	16%	8%	33%	16%	60%	0%	39%	74%	100%
Excess electricity sold to grid (kWh)	-	4,698	4,700	4,698	4,701	4,704	4,715	4,701	4,698	4,698	4,723	4,832	4,702	4,866	4,870
% Excess electricity reduction compared with ZEBs	-	100%	98%	100%	98%	96%	90%	98%	100%	100%	85%	22%	97%	2%	0%
Economic analysis															
Annual electricity cost (Normal rate)	-	$ -	$ (34)	$ (5)	$ (16)	$ (51)	$ (12)	$ 6	$ (23)	$ (2)	$ (67)	$ (52)	$ (33)	$ (147)	$ (171)
Annual gas cost	-	$ -	$ 380	$ 469	$ 511	$ 419	$ 472	$ 463	$ 472	$ 440	$ 482	$ 479	$ 414	$ 289	$ 232
Total annual energy cost	-	$ -	$ 346	$ 465	$ 495	$ 368	$ 461	$ 470	$ 449	$ 438	$ 415	$ 427	$ 381	$ 142	$ 60
% Energy cost saving (Normal rate)	-	-	70%	60%	57%	68%	60%	60%	61%	62%	64%	63%	67%	88%	95%
$ Incremental investment from ASHRAE compliant building	-	-	$ 36,183	$ 33,524	$ 39,747	$ 45,454	$ 33,549	$ 35,615	$ 32,414	$ 32,550	$ 32,029	$ 33,680	$ 32,000	$ 50,653	$ 48,127
% Investment cost reduction compared with the highest invesment strategy	-	-	78%	92%	58%	28%	92%	81%	98%	97%	100%	91%	100%	0%	14%
Payback period (Year)	-	-	44	48	59	57	48	51	45	45	43	46	41	50	44
% Payback period reductioncompared with the longest payback period strategy	-	-	82%	62%	0%	12%	63%	44%	76%	79%	90%	74%	100%	53%	85%
Emission															
Site emission (Ton CO2e)	-	0.48	0.17	0.46	0.42	0.10	0.42	0.52	0.34	0.44	0.06	0.16	0.21	(0.67)	(0.89)
% Site emission (Ton CO2e) reduction compared with ZEBs	-	3%	25%	5%	7%	30%	8%	0%	13%	6%	33%	26%	22%	84%	100%
Source emission (Ton CO2e)	-	0.49	(0.32)	0.43	0.22	(0.65)	0.28	0.67	0.02	0.45	(0.93)	(0.60)	(0.26)	(2.94)	(3.55)
% Reduction compared with existing buildings	-	94%	104%	95%	98%	107%	97%	92%	100%	95%	111%	107%	103%	134%	141%

Table 50. Performances of energy efficiency design strategies and grid-connected PV systems implemented in small houses in Baltimore.

Metrices	Existing	ASHRAE	Wall insulation	Roof insulation	Glazing	Wall, roof, glazing	Daylighting	Thermal Mass	Cooling	Heating	Lighting power density	High efficiency appliance	Thermostat	Passive house	Zero energy building
Electricity consumption															
Annual electricity consumption (kWh)	7,442	4,928	4,887	4,922	4,874	4,824	4,861	4,915	4,885	4,928	4,384	4,515	4,785	3,991	3,886
Annual electricity consumption with typical size grid-connected PV systems	-	433	392	426	378	329	365	419	389	433	(111)	20	290	(504)	(609)
% Annual electricity reduction compared with ZEBs	-	0%	4%	1%	5%	10%	7%	1%	4%	0%	52%	40%	14%	90%	100%
Peak load (kW)	5.2	2.7	2.6	2.7	2.6	2.5	2.6	2.6	2.5	2.7	2.5	2.6	2.6	2.2	2.3
Peak load with PV systems installed	-	2.5	2.4	2.5	2.4	2.3	2.5	2.4	2.3	2.5	2.3	2.4	2.4	2.1	2.1
% Peak load reduction compared with ZEBs	-	0%	13%	0%	25%	35%	0%	18%	37%	0%	34%	21%	4%	100%	90%
Excess PV output and building power load met															
Electricity bought from grid (kWh)	6,004	3,626	3,587	3,619	3,574	3,526	3,567	3,617	3,583	3,626	3,095	3,335	3,488	2,824	2,723
Load met by PV output (kWh)	-	1,302	1,301	1,303	1,299	1,298	1,293	1,298	1,302	1,302	1,289	1,180	1,297	1,166	1,163
% Load met compared to total demand	0%	26%	27%	26%	27%	27%	27%	26%	27%	26%	29%	26%	27%	29%	30%
% Percentage load met by PV output compared with ZEBs	-	7%	13%	9%	14%	20%	12%	7%	13%	7%	87%	0%	26%	82%	100%
Excess electricity sold to grid (kWh)	-	3,193	3,194	3,192	3,196	3,197	3,202	3,197	3,193	3,193	3,206	3,315	3,198	3,329	3,333
% Excess electricity reduction compared with ZEBs	-	100%	99%	100%	97%	97%	93%	97%	99%	100%	90%	13%	96%	3%	0%
Economic analysis															
Annual electricity cost (Normal rate)	-	$ -	$ 45	$ 49	$ 43	$ 38	$ 42	$ 48	$ 45	$ 50	$ (13)	$ 2	$ 33	$ (58)	$ (70)
Annual gas cost	-	$ -	$ 772	$ 836	$ 870	$ 804	$ 838	$ 858	$ 838	$ 777	$ 851	$ 846	$ 767	$ 621	$ 546
Total annual energy cost	-	$ -	$ 817	$ 884	$ 914	$ 842	$ 880	$ 906	$ 882	$ 826	$ 838	$ 849	$ 800	$ 563	$ 476
% Energy cost saving (Normal rate)	-	-	42%	37%	35%	40%	37%	35%	37%	41%	40%	40%	43%	60%	66%
$ Incremental investment from ASHRAE compliant building	-	-	$ 36,183	$ 33,033	$ 39,747	$ 44,963	$ 33,549	$ 35,615	$ 32,276	$ 32,600	$ 32,029	$ 33,680	$ 32,000	$ 50,162	$ 47,548
% Investment cost reduction compared with the highest invesment strategy	-	-	77%	94%	57%	29%	91%	80%	98%	97%	100%	91%	100%	0%	14%
Payback period (Year)	-	-	62	64	81	80	64	72	62	57	57	61	53	60	51
% Payback period reductioncompared with the longest payback period strategy	-	-	65%	59%	0%	4%	57%	32%	64%	82%	82%	68%	94%	72%	100%
Emission															
Site emission (Ton CO2e)	-	1.20	1.10	1.19	1.19	1.09	1.15	1.21	1.17	1.14	0.80	0.90	1.02	0.26	0.11
% Site emission (Ton CO2e) reduction compared with ZEBs	-	1%	10%	2%	2%	11%	6%	0%	4%	7%	37%	28%	17%	86%	100%
Source emission (Ton CO2e)	-	2.06	1.88	2.04	1.96	1.75	1.89	2.05	1.95	1.99	0.69	1.01	1.61	(0.58)	(0.93)
% Reduction compared with existing buildings	-	70%	73%	71%	72%	75%	73%	71%	72%	71%	90%	85%	77%	108%	113%

Table 51. Performances of energy efficiency design strategies and grid-connected PV systems implemented in small houses in Chicago.

Metrices	Existing	ASHRAE	Wall insulation	Roof insulation	Glazing	Wall, roof, glazing	Daylighting	Thermal Mass	Cooling	Heating	Lighting power density	High efficiency appliance	Thermostat	Passive house	Zero energy building
Electricity consumption															
Annual electricity consumption (kWh)	6,937	4,924	4,883	4,925	4,884	4,843	4,858	4,903	4,899	4,924	4,387	4,516	4,809	4,013	3,925
Annual electricity consumption with typical size grid-connected PV systems	-	603	562	604	563	522	537	582	578	603	66	195	488	(308)	(396)
% Annual electricity reduction compared with ZEBs	-	0%	4%	0%	4%	8%	7%	2%	3%	0%	54%	41%	12%	91%	100%
Peak load (kW)	4.5	2.5	2.5	2.5	2.4	2.4	2.4	2.5	2.4	2.5	2.4	2.4	2.5	2.1	2.1
Peak load with PV systems installed	-	2.3	2.2	2.3	2.2	2.1	2.2	2.2	2.1	2.3	2.0	2.2	2.2	2.0	1.9
% Peak load reduction compared with ZEBs	-	2%	26%	0%	33%	42%	28%	17%	37%	2%	63%	28%	23%	86%	100%
Excess PV output and building power load met															
Electricity bought from grid (kWh)	5,494	3,613	3,574	3,614	3,577	3,538	3,557	3,597	3,588	3,613	3,091	3,325	3,504	2,838	2,754
Load met by PV output (kWh)	-	1,311	1,309	1,311	1,307	1,305	1,301	1,305	1,310	1,311	1,296	1,191	1,305	1,175	1,171
% Load met compared to total demand	0%	27%	27%	27%	27%	27%	27%	27%	27%	27%	30%	26%	27%	29%	30%
% Percentage load met by PV output compared with ZEBs	-	7%	13%	7%	12%	17%	12%	8%	11%	7%	92%	0%	22%	84%	100%
Excess electricity sold to grid (kWh)	-	3,010	3,011	3,010	3,014	3,016	3,020	3,016	3,011	3,010	3,025	3,130	3,016	3,146	3,150
% Excess electricity reduction compared with ZEBs	-	100%	99%	100%	97%	96%	92%	96%	100%	100%	89%	14%	96%	3%	0%
Economic analysis															
Annual electricity cost (Normal rate)	-	$ -	$ 64	$ 69	$ 65	$ 60	$ 62	$ 67	$ 66	$ 69	$ 8	$ 22	$ 56	$ (35)	$ (45)
Annual gas cost	-	$ -	$ 1,021	$ 1,097	$ 1,134	$ 1,056	$ 1,100	$ 1,130	$ 1,100	$ 1,017	$ 1,114	$ 1,109	$ 1,020	$ 839	$ 752
Total annual energy cost	-	$ -	$ 1,085	$ 1,166	$ 1,199	$ 1,116	$ 1,162	$ 1,197	$ 1,166	$ 1,086	$ 1,121	$ 1,131	$ 1,076	$ 803	$ 707
% Energy cost saving (Normal rate)	-	-	35%	30%	28%	33%	30%	28%	30%	35%	33%	32%	35%	52%	58%
$ Incremental investment from ASHRAE compliant building	-	-	$ 36,183	$ 32,904	$ 39,747	$ 44,834	$ 33,549	$ 35,615	$ 32,253	$ 32,750	$ 32,029	$ 33,680	$ 32,000	$ 50,033	$ 47,546
% Investment cost reduction compared with the highest invesment strategy	-	-	77%	95%	57%	29%	91%	80%	99%	96%	100%	91%	100%	0%	14%
Payback period (Year)	-	-	62	66	85	82	67	76	65	57	59	63	54	58	50
% Payback period reductioncompared with the longest payback period strategy	-	-	64%	54%	0%	10%	52%	26%	58%	80%	74%	62%	87%	76%	100%
Emission															
Site emission (Ton CO2e)	-	1.60	1.49	1.60	1.61	1.50	1.55	1.62	1.58	1.52	1.21	1.30	1.43	0.64	0.48
% Site emission (Ton CO2e) reduction compared with ZEBs	-	1%	11%	2%	1%	11%	6%	0%	3%	9%	36%	28%	16%	86%	100%
Source emission (Ton CO2e)	-	2.79	2.60	2.79	2.73	2.53	2.62	2.77	2.72	2.70	1.44	1.76	2.41	0.17	(0.15)
% Reduction compared with existing buildings	-	59%	62%	59%	60%	63%	62%	59%	60%	61%	79%	74%	65%	98%	102%

Table 52. Performances of energy efficiency design strategies and grid-connected PV systems implemented in small houses in Duluth.

Metrices	Existing	ASHRAE	Wall insulation	Roof insulation	Glazing	Wall, roof, glazing	Daylighting	Thermal Mass	Cooling	Heating	Lighting power density	High efficiency appliance	Thermostat	Passive house	Zero energy building
Electricity consumption															
Annual electricity consumption (kWh)	6,468	5,042	5,038	5,041	5,031	5,026	4,972	5,040	5,037	5,042	4,518	4,645	4,985	4,116	4,080
Annual electricity consumption with typical size grid-connected PV systems	-	638	634	638	628	622	568	636	633	638	114	241	581	(287)	(324)
% Annual electricity reduction compared with ZEBs	-	0%	0%	0%	1%	2%	7%	0%	1%	0%	55%	41%	6%	96%	100%
Peak load (kW)	4.2	2.2	2.2	2.2	2.0	2.0	2.0	2.1	2.1	2.2	1.9	2.1	2.0	2.0	1.9
Peak load with PV systems installed	-	1.8	1.8	1.8	1.7	1.7	1.6	1.7	1.7	1.8	1.5	1.7	1.6	1.7	1.5
% Peak load reduction compared with ZEBs	-	0%	3%	0%	37%	40%	49%	22%	30%	0%	87%	32%	51%	43%	100%
Excess PV output and building power load met															
Electricity bought from grid (kWh)	4,926	3,649	3,644	3,648	3,640	3,635	3,588	3,650	3,644	3,649	3,139	3,375	3,596	2,859	2,827
Load met by PV output (kWh)	-	1,394	1,393	1,394	1,391	1,391	1,384	1,390	1,393	1,394	1,379	1,270	1,389	1,257	1,253
% Load met compared to total demand	0%	28%	28%	28%	28%	28%	28%	28%	28%	28%	31%	27%	28%	31%	31%
% Percentage load met by PV output compared with ZEBs	-	9%	10%	9%	9%	10%	15%	7%	9%	9%	95%	0%	16%	95%	100%
Excess electricity sold to grid (kWh)	-	3,010	3,010	3,010	3,013	3,013	3,020	3,014	3,011	3,010	3,025	3,134	3,015	3,147	3,151
% Excess electricity reduction compared with ZEBs	-	100%	100%	100%	98%	98%	93%	98%	100%	100%	90%	12%	97%	3%	0%
Economic analysis															
Annual electricity cost (Normal rate)	-	$ -	$ 73	$ 73	$ 72	$ 71	$ 65	$ 73	$ 73	$ 73	$ 13	$ 28	$ 67	$ (33)	$ (37)
Annual gas cost	-	$ -	$ 1,534	$ 1,543	$ 1,566	$ 1,550	$ 1,547	$ 1,597	$ 1,546	$ 1,428	$ 1,567	$ 1,561	$ 1,454	$ 1,276	$ 1,154
Total annual energy cost	-	$ -	$ 1,606	$ 1,616	$ 1,638	$ 1,622	$ 1,612	$ 1,670	$ 1,619	$ 1,501	$ 1,580	$ 1,589	$ 1,521	$ 1,243	$ 1,117
% Energy cost saving (Normal rate)	-	-	24%	24%	23%	24%	24%	21%	24%	29%	26%	25%	28%	42%	47%
$ Incremental investment from ASHRAE compliant building	-	-	$ 32,608	$ 32,646	$ 39,747	$ 41,001	$ 33,549	$ 35,615	$ 32,207	$ 32,750	$ 32,029	$ 33,680	$ 32,000	$ 46,200	$ 43,667
% Investment cost reduction compared with the highest invesment strategy	-	-	96%	95%	45%	37%	89%	75%	99%	95%	100%	88%	100%	0%	18%
Payback period (Year)	-	-	63	64	82	82	65	78	64	53	59	63	53	52	43
% Payback period reductioncompared with the longest payback period strategy	-	-	49%	46%	0%	0%	42%	9%	47%	76%	59%	49%	75%	76%	100%
Emission															
Site emission (Ton CO2e)	-	2.09	2.08	2.09	2.11	2.09	2.04	2.15	2.09	1.97	1.72	1.81	1.96	1.11	0.96
% Site emission (Ton CO2e) reduction compared with ZEBs	-	4%	6%	5%	3%	5%	9%	0%	5%	15%	36%	28%	16%	87%	100%
Source emission (Ton CO2e)	-	3.39	3.36	3.38	3.38	3.35	3.21	3.44	3.37	3.25	2.07	2.39	3.14	0.72	0.49
% Reduction compared with existing buildings	-	53%	53%	53%	53%	53%	55%	52%	53%	54%	71%	67%	56%	90%	93%

Table 53. Performances of energy efficiency design strategies and grid-connected PV systems implemented in medium office buildings in Miami.

Metrices	Existing	ASHRAE	Wall insulation	Roof insulation	Glazing	Wall, roof, glazing	Daylighting	Thermal mass	Cooling	Heating	Desk temp. reset	Thermostat setting	High efficiency appliance	Lighting power density	Zero energy building
Electricity consumption															
Annual electricity consumption (kWh)	979,463	837,353	837,060	835,263	833,968	831,073	808,163	834,111	789,213	837,353	837,631	823,944	776,609	785,867	687,913
Annual electricity consumption with typical size grid-connected PV systems	-	800,005	799,713	797,915	796,620	793,725	770,815	796,763	751,865	800,005	800,283	786,596	739,261	748,519	650,565
% Annual electricity reduction compared with ZEBs	-	0%	0%	2%	2%	4%	20%	2%	32%	0%	0%	9%	41%	35%	100%
Peak load (kW)	314.4	267.4	265.2	265.2	267.9	264.3	254.6	259.9	237.9	267.4	267.4	260.7	248.5	249.3	204.2
Peak load with PV systems installed	-	256.3	255.4	256.0	257.7	255.8	248.9	249.3	230.3	256.3	256.3	254.4	239.0	239.7	198.8
% Peak load reduction compared with ZEBs	-	2%	4%	3%	0%	3%	15%	14%	47%	2%	2%	6%	32%	31%	100%
Excess PV output and building power load met															
Electricity bought from grid (kWh)	946,416	804,902	804,609	802,811	801,517	798,621	775,837	801,660	756,762	804,902	805,180	791,492	744,881	753,592	656,201
Load met by PV output (kWh)	-	32,451	32,451	32,451	32,451	32,451	32,325	32,451	32,451	32,451	32,451	32,451	31,728	32,274	31,712
% Load met compared to total demand	0%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	5%
% Percentage load met by PV output compared with ZEBs	-	0%	0%	1%	2%	4%	17%	2%	32%	0%	0%	9%	29%	32%	100%
Excess electricity sold to grid (kWh)	-	4,897	4,897	4,897	4,897	4,897	5,022	4,897	4,897	4,897	4,897	4,897	5,620	5,074	5,636
% Excess electricity reduction compared with ZEBs	-	100%	100%	100%	100%	100%	83%	100%	100%	100%	100%	100%	2%	76%	0%
Economic analysis															
Annual electricity cost (Normal rate)	-	$ -	$ 80,531	$ 80,350	$ 80,220	$ 79,928	$ 77,621	$ 80,234	$ 75,713	$ 80,561	$ 80,589	$ 79,210	$ 74,444	$ 75,376	$ 65,512
Annual gas cost	-	$ -	$ 640	$ 640	$ 686	$ 665	$ 664	$ 611	$ 659	$ 648	$ 632	$ 608	$ 676	$ 673	$ 1
Total annual energy cost	-	$ -	$ 81,171	$ 80,990	$ 80,906	$ 80,593	$ 78,285	$ 80,845	$ 76,372	$ 81,208	$ 81,220	$ 79,818	$ 75,120	$ 76,049	$ 65,513
% Energy cost saving (Normal rate)	-	-	4%	5%	5%	5%	8%	5%	10%	4%	4%	6%	12%	11%	23%
$ Incremental investment from ASHRAE compliant building	-	-	$ 226,092	$ 235,694	$ 531,170	$ 572,955	$ 274,234	$ 350,731	$ 227,480	$ 219,100	$ 210,000	$ 210,000	$ 279,647	$ 216,661	$ 675,842
% Investment cost reduction compared with the highest invesment strategy	-	-	97%	94%	31%	22%	86%	70%	96%	98%	100%	100%	85%	99%	0%
Payback period (Year)	-	-	59	59	130	131	41	85	26	58	56	41	28	24	35
% Payback period reduction compared with the longest payback period strategy	-	-	67%	67%	0%	0%	84%	43%	98%	68%	70%	85%	96%	100%	90%
Emission															
Site emission (Ton CO2e)	-	607.31	607.06	605.70	604.78	602.56	585.19	604.79	570.82	607.30	607.49	597.08	561.29	568.31	493.13
% Site emission (Ton CO2e) reduction compared with ZEBs	-	0%	0%	2%	2%	4%	19%	2%	32%	0%	0%	9%	40%	34%	100%
Source emission (Ton CO2e)	-	2,041.54	2,040.77	2,036.18	2,032.95	2,025.53	1,967.09	2,033.20	1,918.75	2,041.53	2,042.21	2,007.26	1,886.63	1,910.24	1,659.38
% Reduction compared with existing buildings	-	-175%	-175%	-174%	-173%	-172%	-165%	-174%	-158%	-175%	-175%	-170%	-154%	-157%	-123%

Table 54. Performances of energy efficiency design strategies and grid-connected PV systems implemented in medium office buildings in Phoenix.

Metrices	Existing	ASHRAE	Wall insulation	Roof insulation	Glazing	Wall, roof, glazing	Daylighting	Thermal mass	Cooling	Heating	Desk temp. reset	Thermostat setting	High efficiency appliance	Lighting power density	Zero energy building
Electricity consumption															
Annual electricity consumption (kWh)	962,661	813,566	812,176	811,377	812,472	807,874	785,174	810,706	771,654	813,566	813,245	803,473	753,514	762,468	671,862
Annual electricity consumption with typical size grid-connected PV systems	-	770,873	769,484	768,685	769,780	765,182	742,482	768,014	728,962	770,873	770,553	760,780	710,822	719,776	629,169
% Annual electricity reduction compared with ZEBs	-	0%	1%	2%	1%	4%	20%	2%	30%	0%	0%	7%	42%	36%	100%
Peak load (kW)	369.0	294.7	291.1	294.2	299.6	293.4	281.2	287.4	259.8	294.7	294.7	291.3	275.2	275.7	220.6
Peak load with PV systems installed	-	276.1	272.2	275.5	281.4	276.3	263.2	268.9	244.1	276.1	276.2	273.8	256.5	257.1	212.3
% Peak load reduction compared with ZEBs	-	8%	13%	8%	0%	7%	26%	18%	54%	8%	7%	11%	36%	35%	100%
Excess PV output and building power load met															
Electricity bought from grid (kWh)	925,263	776,797	775,407	774,609	775,704	771,106	748,536	773,938	734,886	776,797	776,477	766,704	717,516	725,888	635,881
Load met by PV output (kWh)	-	36,768	36,768	36,768	36,768	36,768	36,638	36,768	36,768	36,768	36,768	36,768	35,998	36,580	35,981
% Load met compared to total demand	0%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
% Percentage load met by PV output compared with ZEBs	-	0%	1%	1%	1%	4%	18%	2%	29%	0%	0%	7%	31%	33%	100%
Excess electricity sold to grid (kWh)	-	5,924	5,924	5,924	5,924	5,924	6,054	5,924	5,924	5,924	5,924	5,924	6,694	6,112	6,712
% Excess electricity reduction compared with ZEBs	-	100%	100%	100%	100%	100%	83%	100%	100%	100%	100%	100%	2%	76%	0%
Economic analysis															
Annual electricity cost (Normal rate)	-	$ -	$ 77,487	$ 77,407	$ 77,517	$ 77,054	$ 74,768	$ 77,339	$ 73,406	$ 77,627	$ 77,595	$ 76,611	$ 71,580	$ 72,481	$ 63,357
Annual gas cost	-	$ -	$ 746	$ 746	$ 1,143	$ 896	$ 925	$ 885	$ 909	$ 863	$ 780	$ 730	$ 1,005	$ 981	$ 26
Total annual energy cost	-	$ -	$ 78,233	$ 78,153	$ 78,660	$ 77,950	$ 75,693	$ 78,224	$ 74,316	$ 78,490	$ 78,375	$ 77,341	$ 72,584	$ 73,463	$ 63,384
% Energy cost saving (Normal rate)	-	-	6%	6%	5%	6%	9%	6%	10%	5%	5%	7%	12%	11%	23%
$ Incremental investment from ASHRAE compliant building	-	-	$ 226,092	$ 235,694	$ 531,170	$ 572,955	$ 274,234	$ 350,731	$ 228,101	$ 216,950	$ 210,000	$ 210,000	$ 279,647	$ 216,661	$ 674,313
% Investment cost reduction compared with the highest invesment strategy	-	-	97%	94%	31%	22%	86%	70%	96%	99%	100%	100%	85%	99%	0%
Payback period (Year)	-	-	49	50	127	117	38	76	27	50	47	38	27	23	35
% Payback period reduction compared with the longest payback period strategy	-	-	75%	74%	0%	10%	85%	49%	96%	74%	77%	85%	96%	100%	89%
Emission															
Site emission (Ton CO2e)	-	585.58	584.30	583.69	585.07	581.24	564.08	583.38	553.81	585.51	585.16	577.68	540.19	546.94	476.95
% Site emission (Ton CO2e) reduction compared with ZEBs	-	0%	1%	2%	0%	4%	20%	2%	29%	0%	0%	7%	42%	36%	100%
Source emission (Ton CO2e)	-	1,967.61	1,963.82	1,961.79	1,965.18	1,953.08	1,895.22	1,960.28	1,860.71	1,967.54	1,966.60	1,941.60	1,814.59	1,837.39	1,604.84
% Reduction compared with existing buildings	-	-169%	-168%	-168%	-168%	-167%	-159%	-168%	-154%	-169%	-169%	-165%	-148%	-151%	-119%

Table 55. Performances of energy efficiency design strategies and grid-connected PV systems implemented in medium office buildings in Las Vegas.

Metrices	Existing	ASHRAE	Wall insulation	Roof insulation	Glazing	Wall, roof, glazing	Daylighting	Thermal mass	Cooling	Heating	Desk temp. reset	Thermostat setting	High efficiency appliance	Lighting power density	Zero energy building
Electricity consumption															
Annual electricity consumption (kWh)	928,933	779,960	779,418	778,278	778,597	775,534	752,036	778,033	745,941	779,960	775,494	771,954	721,596	730,275	647,846
Annual electricity consumption with typical size grid-connected PV systems	-	737,420	736,878	735,738	736,057	732,994	709,496	735,493	703,401	737,420	732,954	729,414	679,056	687,735	605,306
% Annual electricity reduction compared with ZEBs	-	0%	0%	1%	1%	3%	21%	1%	26%	0%	3%	6%	44%	38%	100%
Peak load (kW)	352.1	286.2	284.1	286.0	291.6	289.4	273.5	275.9	254.7	286.2	286.2	285.5	266.9	267.4	225.1
Peak load with PV systems installed	-	275.3	273.2	275.0	280.7	278.4	262.6	260.6	243.8	275.3	275.3	274.5	256.0	256.5	214.1
% Peak load reduction compared with ZEBs	-	8%	11%	9%	0%	3%	27%	30%	55%	8%	8%	9%	37%	36%	100%
Excess PV output and building power load met															
Electricity bought from grid (kWh)	891,917	743,612	743,071	741,930	742,249	739,186	715,823	741,685	709,594	743,612	739,146	735,606	686,057	694,127	612,325
Load met by PV output (kWh)	-	36,348	36,348	36,348	36,348	36,348	36,213	36,348	36,348	36,348	36,348	36,348	35,539	36,149	35,521
% Load met compared to total demand	0%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
% Percentage load met by PV output compared with ZEBs	-	0%	0%	1%	1%	3%	19%	1%	26%	0%	3%	6%	32%	35%	100%
Excess electricity sold to grid (kWh)	-	6,192	6,192	6,192	6,192	6,192	6,327	6,192	6,192	6,192	6,192	6,192	7,001	6,391	7,019
% Excess electricity reduction compared with ZEBs	-	100%	100%	100%	100%	100%	84%	100%	100%	100%	100%	100%	2%	76%	0%
Economic analysis															
Annual electricity cost (Normal rate)	-	$ -	$ 74,204	$ 74,089	$ 74,121	$ 73,812	$ 71,446	$ 74,064	$ 70,833	$ 74,258	$ 73,808	$ 73,452	$ 68,381	$ 69,255	$ 60,954
Annual gas cost	-	$ -	$ 977	$ 977	$ 1,578	$ 1,234	$ 1,172	$ 1,136	$ 1,140	$ 1,065	$ 956	$ 904	$ 1,293	$ 1,258	$ 95
Total annual energy cost	-	$ -	$ 75,180	$ 75,065	$ 75,699	$ 75,046	$ 72,618	$ 75,201	$ 71,972	$ 75,323	$ 74,765	$ 74,356	$ 69,674	$ 70,513	$ 61,049
% Energy cost saving (Normal rate)	-	-	6%	6%	5%	6%	9%	6%	10%	5%	6%	7%	13%	12%	23%
$ Incremental investment from ASHRAE compliant building	-	-	$ 226,092	$ 235,694	$ 531,170	$ 572,955	$ 274,234	$ 350,731	$ 227,710	$ 218,100	$ 210,000	$ 210,000	$ 279,647	$ 216,661	$ 675,072
% Investment cost reduction compared with the highest invesment strategy	-	-	97%	94%	31%	22%	86%	70%	96%	98%	100%	100%	85%	99%	0%
Payback period (Year)	-	-	50	51	133	124	39	78	30	50	43	39	28	24	36
% Payback period reduction compared with the longest payback period strategy	-	-	76%	75%	0%	9%	86%	50%	95%	76%	83%	86%	96%	100%	89%
Emission															
Site emission (Ton CO2e)	-	560.54	559.90	559.04	560.11	557.31	539.42	559.07	534.75	560.43	556.90	554.14	516.51	523.04	458.95
% Site emission (Ton CO2e) reduction compared with ZEBs	-	0%	1%	1%	0%	3%	21%	1%	25%	0%	3%	6%	43%	37%	100%
Source emission (Ton CO2e)	-	1,882.63	1,881.00	1,878.10	1,879.82	1,871.48	1,811.46	1,877.71	1,795.86	1,882.52	1,870.96	1,861.86	1,733.99	1,756.08	1,544.08
% Reduction compared with existing buildings	-	-166%	-166%	-165%	-166%	-164%	-156%	-165%	-154%	-166%	-164%	-163%	-145%	-148%	-118%

Table 56. Performances of energy efficiency design strategies and grid-connected PV systems implemented in medium office buildings in Baltimore.

Metrices	Existing	ASHRAE	Wall insulation	Roof insulation	Glazing	Wall, roof, glazing	Daylighting	Thermal mass	Cooling	Heating	Desk temp. reset	Thermostat setting	High efficiency appliance	Lighting power density	Zero energy building
Electricity consumption															
Annual electricity consumption (kWh)	861,892	743,593	743,987	743,500	736,799	735,915	693,494	740,012	717,358	743,593	735,289	736,400	686,896	695,292	615,192
Annual electricity consumption with typical size grid-connected PV systems	-	711,784	712,177	711,691	704,989	704,105	661,684	708,202	685,548	711,784	703,479	704,590	655,086	663,482	583,382
% Annual electricity reduction compared with ZEBs	-	0%	0%	0%	6%	6%	39%	3%	21%	0%	7%	6%	44%	38%	100%
Peak load (kW)	311.3	261.1	260.9	259.6	256.1	253.7	238.0	260.2	232.1	261.1	261.6	256.9	242.2	242.9	193.9
Peak load with PV systems installed	-	251.6	251.0	251.4	248.2	246.9	233.8	249.4	227.3	251.6	251.6	244.5	233.1	234.0	189.0
% Peak load reduction compared with ZEBs	-	0%	1%	0%	5%	7%	29%	3%	39%	0%	0%	11%	30%	28%	100%
Excess PV output and building power load met															
Electricity bought from grid (kWh)	833,104	715,255	715,648	715,162	708,461	707,576	665,331	711,674	689,019	715,255	706,950	708,061	659,114	667,088	587,423
Load met by PV output (kWh)	-	28,339	28,339	28,339	28,339	28,339	28,163	28,339	28,339	28,339	28,339	28,339	27,782	28,204	27,768
% Load met compared to total demand	0%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	5%
% Percentage load met by PV output compared with ZEBs	-	0%	0%	0%	5%	6%	36%	3%	20%	0%	6%	6%	33%	35%	100%
Excess electricity sold to grid (kWh)	-	3,471	3,471	3,471	3,471	3,471	3,647	3,471	3,471	3,471	3,471	3,471	4,028	3,606	4,041
% Excess electricity reduction compared with ZEBs	-	100%	100%	100%	100%	100%	69%	100%	100%	100%	100%	100%	2%	76%	0%
Economic analysis															
Annual electricity cost (Normal rate)	-	$ -	$ 71,716	$ 71,667	$ 70,992	$ 70,903	$ 66,632	$ 71,316	$ 69,035	$ 71,677	$ 70,840	$ 70,952	$ 65,967	$ 66,813	$ 58,747
Annual gas cost	-	$ -	$ 2,863	$ 2,863	$ 3,668	$ 2,843	$ 3,642	$ 2,944	$ 3,295	$ 2,898	$ 2,266	$ 2,588	$ 3,759	$ 3,669	$ 1,072
Total annual energy cost	-	$ -	$ 74,579	$ 74,530	$ 74,660	$ 73,746	$ 70,274	$ 74,260	$ 72,329	$ 74,575	$ 73,107	$ 73,540	$ 69,726	$ 70,482	$ 59,819
% Energy cost saving (Normal rate)	-	-	5%	5%	4%	6%	10%	5%	7%	5%	6%	6%	11%	10%	23%
$ Incremental investment from ASHRAE compliant building	-	-	$ 223,835	$ 235,694	$ 531,170	$ 570,698	$ 274,234	$ 350,731	$ 227,342	$ 222,750	$ 210,000	$ 210,000	$ 279,647	$ 216,661	$ 677,097
% Investment cost reduction compared with the highest invesment strategy	-	-	97%	94%	31%	23%	86%	70%	96%	97%	100%	100%	85%	99%	0%
Payback period (Year)	-	-	62	65	151	129	35	90	39	62	41	45	33	28	37
% Payback period reduction compared with the longest payback period strategy	-	-	72%	70%	0%	18%	95%	50%	91%	73%	89%	86%	96%	100%	93%
Emission															
Site emission (Ton CO2e)	-	544.08	543.78	543.41	539.44	537.63	506.58	540.88	524.19	543.53	536.36	537.65	501.74	507.98	443.68
% Site emission (Ton CO2e) reduction compared with ZEBs	-	0%	0%	0%	4%	6%	37%	3%	20%	0%	7%	6%	42%	36%	100%
Source emission (Ton CO2e)	-	1,820.49	1,820.84	1,819.60	1,803.72	1,800.22	1,693.22	1,810.83	1,753.57	1,819.89	1,797.76	1,801.07	1,676.57	1,697.85	1,489.63
% Reduction compared with existing buildings	-	-176%	-176%	-176%	-173%	-173%	-156%	-174%	-166%	-176%	-172%	-173%	-154%	-157%	-126%

Table 57. Performances of energy efficiency design strategies and grid-connected PV systems implemented in medium office buildings in Chicago.

Metrices	Existing	ASHRAE	Wall insulation	Roof insulation	Glazing	Wall, roof, glazing	Daylighting	Thermal mass	Cooling	Heating	Desk temp. reset	Thermostat setting	High efficiency appliance	Lighting power density	Zero energy building
Electricity consumption															
Annual electricity consumption (kWh)	841,707	710,340	710,884	710,163	705,658	702,898	662,710	709,011	692,229	710,340	706,238	705,846	656,166	664,248	600,014
Annual electricity consumption with typical size grid-connected PV systems	-	679,345	679,889	679,168	674,663	671,903	631,715	678,017	661,235	679,345	675,243	674,851	625,171	633,254	569,019
% Annual electricity reduction compared with ZEBs	-	0%	0%	1%	5%	7%	43%	2%	17%	0%	4%	5%	49%	42%	100%
Peak load (kW)	291.9	250.4	251.1	250.3	244.4	240.3	227.2	248.9	226.4	250.4	250.6	243.9	230.5	232.1	185.0
Peak load with PV systems installed	-	241.7	242.4	241.5	235.3	229.8	223.3	236.3	217.6	241.7	241.8	233.1	221.7	223.3	175.1
% Peak load reduction compared with ZEBs	-	1%	0%	1%	10%	19%	28%	9%	37%	1%	1%	14%	31%	28%	100%
Excess PV output and building power load met															
Electricity bought from grid (kWh)	813,435	682,519	683,063	682,342	677,837	675,077	635,071	681,191	664,409	682,519	678,417	678,025	628,925	636,567	572,786
Load met by PV output (kWh)	-	27,821	27,821	27,821	27,821	27,821	27,639	27,821	27,821	27,821	27,821	27,821	27,241	27,682	27,228
% Load met compared to total demand	0%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	5%
% Percentage load met by PV output compared with ZEBs	-	0%	0%	1%	5%	7%	41%	2%	17%	0%	4%	4%	38%	41%	100%
Excess electricity sold to grid (kWh)	-	3,174	3,174	3,174	3,174	3,174	3,356	3,174	3,174	3,174	3,174	3,174	3,754	3,313	3,767
% Excess electricity reduction compared with ZEBs	-	100%	100%	100%	100%	100%	69%	100%	100%	100%	100%	100%	2%	77%	0%
Economic analysis															
Annual electricity cost (Normal rate)	-	$ -	$ 68,465	$ 68,392	$ 67,939	$ 67,661	$ 63,614	$ 68,276	$ 66,586	$ 68,410	$ 67,997	$ 67,957	$ 62,955	$ 63,769	$ 57,300
Annual gas cost	-	$ -	$ 4,391	$ 4,391	$ 5,520	$ 5,442	$ 5,401	$ 4,423	$ 4,986	$ 4,330	$ 3,724	$ 4,095	$ 5,542	$ 5,438	$ 2,280
Total annual energy cost	-	$ -	$ 72,856	$ 72,784	$ 73,458	$ 73,103	$ 69,015	$ 72,699	$ 71,572	$ 72,740	$ 71,721	$ 72,053	$ 68,497	$ 69,207	$ 59,580
% Energy cost saving (Normal rate)	-	-	5%	5%	4%	4%	10%	5%	6%	5%	6%	6%	10%	10%	22%
$ Incremental investment from ASHRAE compliant building	-	-	$ 223,835	$ 235,694	$ 531,170	$ 570,698	$ 274,234	$ 350,731	$ 227,112	$ 225,100	$ 210,000	$ 210,000	$ 279,647	$ 216,661	$ 679,217
% Investment cost reduction compared with the highest invesment strategy	-	-	97%	95%	32%	23%	86%	70%	96%	97%	100%	100%	85%	99%	0%
Payback period (Year)	-	-	61	63	174	167	37	92	46	60	44	47	35	30	40
% Payback period reduction compared with the longest payback period strategy	-	-	78%	77%	0%	5%	95%	57%	89%	79%	90%	88%	96%	100%	93%
Emission															
Site emission (Ton CO_2e)	-	521.82	521.41	520.87	519.01	516.81	486.29	520.04	508.09	520.92	516.97	517.19	481.53	487.51	434.46
% Site emission (Ton CO_2e) reduction compared with ZEBs	-	0%	0%	1%	3%	5%	40%	2%	15%	1%	5%	5%	46%	39%	100%
Source emission (Ton CO_2e)	-	1,740.30	1,740.79	1,738.95	1,729.16	1,722.00	1,619.43	1,736.06	1,694.10	1,739.31	1,727.93	1,727.49	1,602.96	1,623.41	1,454.81
% Reduction compared with existing buildings	-	-168%	-169%	-168%	-167%	-166%	-150%	-168%	-161%	-168%	-167%	-166%	-147%	-150%	-124%

Table 58. Performances of energy efficiency design strategies and grid-connected PV systems implemented in medium office buildings in Duluth.

Metrices	Existing	ASHRAE	Wall insulation	Roof insulation	Glazing	Wall, roof, glazing	Daylighting	Thermal mass	Cooling	Heating	Desk temp. reset	Thermostat setting	High efficiency appliance	Lighting power density	Zero energy building
Electricity consumption															
Annual electricity consumption (kWh)	815,633	679,600	680,026	679,632	675,897	674,954	634,969	678,395	668,979	679,600	673,302	677,037	627,699	635,391	580,360
Annual electricity consumption with typical size grid-connected PV systems	-	649,643	650,070	649,676	645,941	644,997	605,013	648,438	639,023	649,643	643,345	647,081	597,742	605,435	550,404
% Annual electricity reduction compared with ZEBs	-	0%	0%	0%	4%	5%	45%	2%	11%	0%	7%	3%	53%	45%	100%
Peak load (kW)	279.8	239.6	241.6	239.7	230.7	225.2	217.1	237.4	217.5	239.6	240.0	232.2	220.2	221.8	175.1
Peak load with PV systems installed	-	230.4	232.4	230.5	219.3	212.2	210.9	224.4	208.4	230.4	230.9	221.5	211.1	212.7	165.7
% Peak load reduction compared with ZEBs	-	3%	0%	3%	20%	30%	32%	12%	36%	3%	2%	16%	32%	30%	100%
Excess PV output and building power load met															
Electricity bought from grid (kWh)	788,436	652,843	653,269	652,875	649,141	648,197	608,390	651,638	642,223	652,843	646,545	650,280	601,507	608,770	554,183
Load met by PV output (kWh)	-	26,757	26,757	26,757	26,757	26,757	26,580	26,757	26,757	26,757	26,757	26,757	26,191	26,621	26,178
% Load met compared to total demand	0%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	5%
% Percentage load met by PV output compared with ZEBs	-	0%	0%	0%	4%	5%	44%	2%	11%	0%	7%	3%	41%	44%	100%
Excess electricity sold to grid (kWh)	-	3,200	3,200	3,200	3,200	3,200	3,377	3,200	3,200	3,200	3,200	3,200	3,765	3,335	3,779
% Excess electricity reduction compared with ZEBs	-	100%	100%	100%	100%	100%	69%	100%	100%	100%	100%	100%	2%	77%	0%
Economic analysis															
Annual electricity cost (Normal rate)	-	$ -	$ 65,462	$ 65,422	$ 65,046	$ 64,951	$ 60,925	$ 65,298	$ 64,350	$ 65,419	$ 64,785	$ 65,161	$ 60,193	$ 60,967	$ 55,426
Annual gas cost	-	$ -	$ 7,119	$ 7,119	$ 7,478	$ 9,035	$ 8,630	$ 7,325	$ 7,991	$ 6,878	$ 6,684	$ 6,912	$ 8,769	$ 8,633	$ 3,881
Total annual energy cost	-	$ -	$ 72,581	$ 72,542	$ 72,524	$ 73,986	$ 69,555	$ 72,623	$ 72,340	$ 72,297	$ 71,469	$ 72,073	$ 68,962	$ 69,600	$ 59,306
% Energy cost saving (Normal rate)	-	-	5%	5%	5%	3%	9%	5%	5%	5%	6%	6%	10%	9%	22%
$ Incremental investment from ASHRAE compliant building	-	-	$ 223,835	$ 235,694	$ 531,170	$ 570,698	$ 274,234	$ 350,731	$ 227,135	$ 228,050	$ 210,000	$ 210,000	$ 279,647	$ 216,661	$ 682,190
% Investment cost reduction compared with the highest invesment strategy	-	-	97%	95%	32%	24%	86%	70%	96%	96%	100%	100%	85%	99%	0%
Payback period (Year)	-	-	58	61	136	234	40	92	56	55	42	48	37	32	40
% Payback period reduction compared with the longest payback period strategy	-	-	87%	86%	48%	0%	96%	70%	88%	88%	95%	92%	97%	100%	96%
Emission															
Site emission (Ton CO2e)	-	503.45	502.57	502.28	499.94	501.37	470.51	501.62	495.40	501.92	496.88	500.02	465.19	470.83	422.56
% Site emission (Ton CO2e) reduction compared with ZEBs	-	-1%	0%	0%	3%	2%	40%	1%	9%	1%	7%	3%	47%	40%	100%
Source emission (Ton CO2e)	-	1,669.06	1,668.84	1,667.83	1,658.85	1,658.79	1,556.19	1,664.99	1,641.97	1,667.39	1,651.03	1,660.90	1,537.85	1,557.27	1,409.75
% Reduction compared with existing buildings	-	-163%	-163%	-163%	-161%	-161%	-145%	-162%	-159%	-163%	-160%	-162%	-142%	-145%	-122%

Table 59. Performances of energy efficiency design strategies and grid-connected PV systems implemented in factory buildings in Miami.

Metrices	Existing	ASHRAE	Wall insulation	Roof insulation	Glazing	Wall, roof, glazing	Daylighting	Thermal mass	Cooling	Heating	Desk temp. reset	Thermostat setting	High efficiency appliance	Lighting power density	Zero energy building
Electricity consumption															
Annual electricity consumption (kWh)	1,342,339	1,069,754	1,068,716	1,069,425	1,069,775	1,070,440	1,062,026	1,031,706	1,013,112	1,069,754	1,064,500	1,049,362	1,027,460	994,781	894,318
Annual electricity consumption with typical size grid-connected PV systems	-	356,088	355,050	355,759	356,109	356,774	348,360	318,040	299,446	356,088	350,834	335,696	313,794	281,115	180,652
% Annual electricity reduction compared with ZEBs	-	0%	1%	1%	0%	0%	5%	22%	33%	0%	3%	12%	24%	43%	100%
Peak load (kW)	562.3	466.0	466.3	465.5	465.9	465.5	463.1	422.6	418.4	466.0	465.9	457.0	448.9	434.9	370.8
Peak load with PV systems installed	-	393.8	393.0	393.9	394.5	395.8	389.2	359.0	347.5	393.8	394.0	384.4	376.2	364.4	298.3
% Peak load reduction compared with ZEBs	-	2%	3%	2%	1%	0%	7%	38%	50%	2%	2%	12%	20%	32%	100%
Excess PV output and building power load met															
Electricity bought from grid (kWh)	844,389	592,160	591,083	591,866	592,200	592,757	585,855	558,782	541,867	592,160	588,466	573,424	557,405	531,533	453,271
Load met by PV output (kWh)	-	477,594	477,633	477,559	477,575	477,683	476,171	472,923	471,245	477,594	476,035	475,939	470,055	463,248	441,047
% Load met compared to total demand	0%	45%	45%	45%	45%	45%	45%	46%	47%	45%	45%	45%	46%	47%	49%
% Percentage load met by PV output compared with ZEBs	-	0%	1%	1%	0%	0%	5%	26%	40%	0%	2%	16%	24%	41%	100%
Excess electricity sold to grid (kWh)	-	236,072	236,033	236,107	236,091	235,983	237,495	240,743	242,421	236,072	237,631	237,727	243,611	250,418	272,619
% Excess electricity reduction compared with ZEBs	-	100%	100%	100%	100%	100%	96%	87%	82%	100%	96%	95%	79%	61%	0%
Economic analysis															
Annual electricity cost (Normal rate)	-	$ -	$ 23,682	$ 23,729	$ 23,752	$ 23,797	$ 23,236	$ 21,213	$ 19,973	$ 23,751	$ 23,401	$ 22,391	$ 20,930	$ 18,750	$ 12,049
Annual gas cost	-	$ -	$ 3,798	$ 3,798	$ 3,958	$ 3,868	$ 3,932	$ 2,549	$ 3,917	$ 3,433	$ 3,619	$ 3,329	$ 3,944	$ 3,965	$ 2,732
Total annual energy cost	-	$ -	$ 27,480	$ 27,527	$ 27,710	$ 27,665	$ 27,167	$ 23,762	$ 23,890	$ 27,184	$ 27,019	$ 25,720	$ 24,874	$ 22,715	$ 14,782
% Energy cost saving (Normal rate)	-	-	63%	63%	63%	63%	64%	68%	68%	64%	64%	66%	67%	70%	80%
$ Incremental investment from ASHRAE compliant building	-	-	$ 3,660,505	$ 3,654,944	$ 3,596,840	$ 3,912,289	$ 3,629,120	$ 3,800,251	$ 3,527,554	$ 3,530,800	$ 3,500,000	$ 3,500,000	$ 3,640,000	$ 3,513,389	$ 4,124,032
% Investment cost reduction compared with the highest invesment strategy	-	-	74%	75%	84%	34%	79%	52%	96%	95%	100%	100%	78%	98%	0%
Payback period (Year)	-	-	77	77	76	82	75	74	69	73	73	71	72	67	68
% Payback period reduction compared with the longest payback period strategy	-	-	36%	37%	43%	0%	44%	55%	88%	57%	63%	75%	65%	100%	91%
Emission															
Site emission (Ton CO2e)	-	279.66	278.58	279.11	279.78	280.06	273.84	247.41	236.72	278.45	274.93	262.74	247.67	222.95	143.73
% Site emission (Ton CO2e) reduction compared with ZEBs	-	0%	1%	1%	0%	0%	5%	24%	32%	1%	4%	13%	24%	42%	100%
Source emission (Ton CO2e)	-	918.90	915.93	917.74	919.07	920.52	899.23	818.14	774.43	917.59	904.69	865.29	811.10	727.80	468.20
% Reduction compared with existing buildings	-	10%	11%	11%	10%	10%	12%	20%	25%	11%	12%	16%	21%	29%	54%

Table 60. Performances of energy efficiency design strategies and grid-connected PV systems implemented in factory buildings in Phoenix.

Metrices	Existing	ASHRAE	Wall insulation	Roof insulation	Glazing	Wall, roof, glazing	Daylighting	Thermal mass	Cooling	Heating	Desk temp. reset	Thermostat setting	High efficiency appliance	Lighting power density	Zero energy building
Electricity consumption															
Annual electricity consumption (kWh)	1,360,710	1,052,086	1,052,168	1,051,588	1,051,903	1,053,071	1,043,933	1,036,127	1,001,902	1,052,086	1,048,472	1,039,807	1,008,157	974,014	887,819
Annual electricity consumption with typical size grid-connected PV systems	-	207,436	207,518	206,938	207,253	208,421	199,283	191,477	157,253	207,436	203,822	195,157	163,508	129,365	43,169
% Annual electricity reduction compared with ZEBs	-	1%	1%	1%	1%	0%	6%	10%	31%	1%	3%	8%	27%	48%	100%
Peak load (kW)	568.6	424.4	423.9	424.3	424.5	424.5	420.8	420.1	385.9	424.4	424.4	424.4	406.5	391.6	344.3
Peak load with PV systems installed	-	365.2	362.5	364.9	365.4	365.3	364.4	349.3	342.5	365.2	365.3	353.5	350.0	336.3	295.0
% Peak load reduction compared with ZEBs	-	0%	4%	1%	0%	0%	1%	23%	33%	0%	0%	17%	22%	41%	100%
Excess PV output and building power load met															
Electricity bought from grid (kWh)	766,522	494,388	494,126	494,024	494,289	494,878	488,899	480,926	454,990	494,388	491,965	486,288	462,690	439,118	389,888
Load met by PV output (kWh)	-	557,698	558,042	557,564	557,614	558,193	555,034	555,200	546,912	557,698	556,507	553,519	545,467	534,896	497,931
% Load met compared to total demand	0%	53%	53%	53%	53%	53%	53%	54%	55%	53%	53%	53%	54%	55%	56%
% Percentage load met by PV output compared with ZEBs	-	0%	1%	0%	0%	0%	5%	19%	51%	0%	2%	7%	36%	62%	100%
Excess electricity sold to grid (kWh)	-	286,952	286,608	287,085	287,035	286,456	289,616	289,449	297,737	286,952	288,143	291,130	299,183	309,753	346,719
% Excess electricity reduction compared with ZEBs	-	99%	100%	99%	99%	100%	95%	95%	81%	99%	97%	92%	79%	61%	0%
Economic analysis															
Annual electricity cost (Normal rate)	-	$ -	$ 13,841	$ 13,803	$ 13,824	$ 13,902	$ 13,292	$ 12,772	$ 10,489	$ 13,836	$ 13,595	$ 13,017	$ 10,906	$ 8,629	$ 2,879
Annual gas cost	-	$ -	$ 2,244	$ 2,244	$ 2,448	$ 2,336	$ 2,405	$ 1,732	$ 2,393	$ 2,140	$ 2,209	$ 1,971	$ 2,437	$ 2,469	$ 1,641
Total annual energy cost	-	$ -	$ 16,085	$ 16,046	$ 16,271	$ 16,238	$ 15,697	$ 14,503	$ 12,881	$ 15,976	$ 15,803	$ 14,988	$ 13,343	$ 11,097	$ 4,520
% Energy cost saving (Normal rate)	-	-	78%	78%	78%	78%	78%	80%	82%	78%	78%	79%	82%	85%	94%
$ Incremental investment from ASHRAE compliant building	-	-	$ 3,660,505	$ 3,654,944	$ 3,596,840	$ 3,912,289	$ 3,629,120	$ 3,800,251	$ 3,522,034	$ 3,505,600	$ 3,500,000	$ 3,500,000	$ 3,640,000	$ 3,513,389	$ 4,093,312
% Investment cost reduction compared with the highest invesment strategy	-	-	73%	74%	84%	31%	78%	49%	96%	99%	100%	100%	76%	98%	0%
Payback period (Year)	-	-	65	65	64	69	64	65	59	62	62	61	61	57	60
% Payback period reduction compared with the longest payback period strategy	-	-	38%	39%	45%	0%	46%	33%	85%	61%	63%	70%	65%	100%	76%
Emission															
Site emission (Ton CO2e)	-	163.19	162.88	162.44	163.19	163.79	157.04	149.45	125.15	162.56	159.99	152.83	130.00	104.20	36.80
% Site emission (Ton CO2e) reduction compared with ZEBs	-	0%	1%	1%	0%	0%	5%	11%	30%	1%	3%	9%	27%	47%	100%
Source emission (Ton CO2e)	-	535.60	535.40	533.93	535.28	537.96	514.84	493.10	407.60	534.92	525.88	503.13	423.67	336.67	114.57
% Reduction compared with existing buildings	-	48%	48%	49%	48%	48%	50%	53%	61%	49%	49%	52%	59%	68%	89%

Table 61. Performances of energy efficiency design strategies and grid-connected PV systems implemented in factory buildings in Las Vegas.

Metrices	Existing	ASHRAE	Wall insulation	Roof insulation	Glazing	Wall, roof, glazing	Daylighting	Thermal mass	Cooling	Heating	Desk temp. reset	Thermostat setting	High efficiency appliance	Lighting power density	Zero energy building
Electricity consumption															
Annual electricity consumption (kWh)	1,314,563	1,015,180	1,015,042	1,014,879	1,014,856	1,014,360	1,007,385	991,597	973,380	1,015,180	1,008,647	1,004,698	972,781	939,741	861,650
Annual electricity consumption with typical size grid-connected PV systems	-	161,776	161,638	161,475	161,452	160,956	153,981	138,192	119,975	161,776	155,243	151,293	119,377	86,336	8,245
% Annual electricity reduction compared with ZEBs	-	0%	0%	0%	0%	1%	5%	15%	27%	0%	4%	7%	28%	49%	100%
Peak load (kW)	575.5	429.2	429.1	429.2	429.3	429.1	426.6	408.4	389.5	429.2	429.2	429.2	411.5	396.9	348.4
Peak load with PV systems installed	-	357.4	356.7	357.4	357.5	356.8	355.3	339.3	323.8	357.4	356.3	357.8	340.0	325.5	280.4
% Peak load reduction compared with ZEBs	-	1%	1%	1%	0%	1%	3%	24%	44%	1%	2%	0%	23%	42%	100%
Excess PV output and building power load met															
Electricity bought from grid (kWh)	737,682	482,191	481,956	481,964	482,003	481,492	477,380	462,922	451,200	482,191	478,746	475,566	453,962	433,116	391,044
Load met by PV output (kWh)	-	532,990	533,086	532,915	532,853	532,868	530,005	528,675	522,180	532,990	529,902	529,132	518,819	506,625	470,606
% Load met compared to total demand	0%	53%	53%	53%	53%	53%	53%	53%	54%	53%	53%	53%	53%	54%	55%
% Percentage load met by PV output compared with ZEBs	-	0%	1%	0%	0%	1%	5%	38%	54%	0%	2%	8%	39%	67%	100%
Excess electricity sold to grid (kWh)	-	320,415	320,318	320,489	320,551	320,536	323,399	324,729	331,224	320,415	323,503	324,273	334,586	346,780	382,798
% Excess electricity reduction compared with ZEBs	-	100%	100%	100%	100%	100%	95%	93%	83%	100%	95%	94%	77%	58%	0%
Economic analysis															
Annual electricity cost (Normal rate)	-	$ -	$ 10,781	$ 10,770	$ 10,769	$ 10,736	$ 10,271	$ 9,217	$ 8,002	$ 10,790	$ 10,355	$ 10,091	$ 7,962	$ 5,759	$ 550
Annual gas cost	-	$ -	$ 3,236	$ 3,236	$ 3,440	$ 3,311	$ 3,398	$ 2,614	$ 3,375	$ 2,978	$ 3,125	$ 2,859	$ 3,427	$ 3,467	$ 2,386
Total annual energy cost	-	$ -	$ 14,017	$ 14,006	$ 14,209	$ 14,046	$ 13,668	$ 11,832	$ 11,377	$ 13,769	$ 13,479	$ 12,950	$ 11,390	$ 9,226	$ 2,936
% Energy cost saving (Normal rate)	-	-	80%	80%	80%	80%	81%	83%	84%	81%	81%	82%	84%	87%	96%
$ Incremental investment from ASHRAE compliant building	-	-	$ 3,660,505	$ 3,654,944	$ 3,596,840	$ 3,912,289	$ 3,629,120	$ 3,800,251	$ 3,521,712	$ 3,506,500	$ 3,500,000	$ 3,500,000	$ 3,640,000	$ 3,513,389	$ 4,093,890
% Investment cost reduction compared with the highest invesment strategy	-	-	73%	74%	84%	31%	78%	49%	96%	99%	100%	100%	76%	98%	0%
Payback period (Year)	-	-	64	64	63	69	63	64	59	61	61	60	61	57	60
% Payback period reduction compared with the longest payback period strategy	-	-	38%	39%	45%	0%	46%	38%	81%	63%	66%	71%	65%	100%	72%
Emission															
Site emission (Ton CO2e)	-	131.02	130.57	130.45	130.94	130.24	125.17	111.25	99.34	130.03	125.45	121.79	99.01	74.07	12.19
% Site emission (Ton CO2e) reduction compared with ZEBs	-	0%	0%	0%	0%	1%	5%	17%	27%	1%	5%	8%	27%	48%	100%
Source emission (Ton CO2e)	-	421.80	421.07	420.66	421.15	419.54	401.98	359.58	315.18	420.73	404.46	393.67	313.80	229.63	27.51
% Reduction compared with existing buildings	-	58%	58%	58%	58%	58%	60%	64%	69%	58%	60%	61%	69%	77%	97%

Table 62. Performances of energy efficiency design strategies and grid-connected PV systems implemented in factory buildings in Baltimore.

Metrices	Existing	ASHRAE	Wall insulation	Roof insulation	Glazing	Wall, roof, glazing	Daylighting	Thermal mass	Cooling	Heating	Desk temp. reset	Thermostat setting	High efficiency appliance	Lighting power density	Zero energy building
Electricity consumption															
Annual electricity consumption (kWh)	1,342,339	1,069,754	1,068,716	1,069,425	1,069,775	1,070,440	1,062,026	1,031,706	1,013,112	1,069,754	1,064,500	1,049,362	1,027,460	994,781	894,318
Annual electricity consumption with typical size grid-connected PV systems	-	356,088	355,050	355,759	356,109	356,774	348,360	318,040	299,446	356,088	350,834	335,696	313,794	281,115	180,652
% Annual electricity reduction compared with ZEBs	-	0%	1%	1%	0%	0%	5%	22%	33%	0%	3%	12%	24%	43%	100%
Peak load (kW)	562.3	466.0	466.3	465.5	465.9	465.5	463.1	422.6	418.4	466.0	465.9	457.0	448.9	434.9	370.8
Peak load with PV systems installed	-	393.8	393.0	393.9	394.5	395.8	389.2	359.0	347.5	393.8	394.0	384.4	376.2	364.4	298.3
% Peak load reduction compared with ZEBs	-	2%	3%	2%	1%	0%	7%	38%	50%	2%	2%	12%	20%	32%	100%
Excess PV output and building power load met															
Electricity bought from grid (kWh)	844,389	592,160	591,083	591,866	592,200	592,757	585,855	558,782	541,867	592,160	588,466	573,424	557,405	531,533	453,271
Load met by PV output (kWh)	-	477,594	477,633	477,559	477,575	477,683	476,171	472,923	471,245	477,594	476,035	475,939	470,055	463,248	441,047
% Load met compared to total demand	0%	45%	45%	45%	45%	45%	45%	46%	47%	45%	45%	45%	46%	47%	49%
% Percentage load met by PV output compared with ZEBs	-	0%	1%	1%	0%	0%	5%	26%	40%	0%	2%	16%	24%	41%	100%
Excess electricity sold to grid (kWh)	-	236,072	236,033	236,107	236,091	235,983	237,495	240,743	242,421	236,072	237,631	237,727	243,611	250,418	272,619
% Excess electricity reduction compared with ZEBs	-	100%	100%	100%	100%	100%	96%	87%	82%	100%	96%	95%	79%	61%	0%
Economic analysis															
Annual electricity cost (Normal rate)	-	$ -	$ 23,682	$ 23,729	$ 23,752	$ 23,797	$ 23,236	$ 21,213	$ 19,973	$ 23,751	$ 23,401	$ 22,391	$ 20,930	$ 18,750	$ 12,049
Annual gas cost	-	$ -	$ 3,798	$ 3,798	$ 3,958	$ 3,868	$ 3,932	$ 2,549	$ 3,917	$ 3,433	$ 3,619	$ 3,329	$ 3,944	$ 3,965	$ 2,732
Total annual energy cost	-	$ -	$ 27,480	$ 27,527	$ 27,710	$ 27,665	$ 27,167	$ 23,762	$ 23,890	$ 27,184	$ 27,019	$ 25,720	$ 24,874	$ 22,715	$ 14,782
% Energy cost saving (Normal rate)	-	-	63%	63%	63%	63%	64%	68%	68%	64%	64%	66%	67%	70%	80%
$ Incremental investment from ASHRAE compliant building	-	-	$ 3,637,993	$ 3,654,944	$ 3,596,840	$ 3,889,777	$ 3,629,120	$ 3,800,251	$ 3,520,171	$ 3,507,900	$ 3,500,000	$ 3,500,000	$ 3,640,000	$ 3,513,389	$ 4,071,237
% Investment cost reduction compared with the highest invesment strategy	-	-	76%	73%	83%	32%	77%	47%	96%	99%	100%	100%	75%	98%	0%
Payback period (Year)	-	-	76	77	76	82	75	74	69	73	73	71	72	67	67
% Payback period reduction compared with the longest payback period strategy	-	-	38%	35%	41%	0%	42%	53%	89%	59%	62%	75%	64%	100%	97%
Emission															
Site emission (Ton CO2e)	-	279.66	278.58	279.11	279.78	280.06	273.84	247.41	236.72	278.45	274.93	262.74	247.67	222.95	143.73
% Site emission (Ton CO2e) reduction compared with ZEBs	-	0%	1%	1%	0%	0%	5%	24%	32%	1%	4%	13%	24%	42%	100%
Source emission (Ton CO2e)	-	918.90	915.93	917.74	919.07	920.52	899.23	818.14	774.43	917.59	904.69	865.29	811.10	727.80	468.20
% Reduction compared with existing buildings	-	10%	11%	11%	10%	10%	12%	20%	25%	11%	12%	16%	21%	29%	54%

Table 63. Performances of energy efficiency design strategies and grid-connected PV systems implemented in factory buildings in Chicago.

Metrices	Existing	ASHRAE	Wall insulation	Roof insulation	Glazing	Wall, roof, glazing	Daylighting	Thermal mass	Cooling	Heating	Desk temp. reset	Thermostat setting	High efficiency appliance	Lighting power density	Zero energy building
Electricity consumption															
Annual electricity consumption (kWh)	1,165,200	914,365	914,548	914,298	912,486	912,453	897,520	905,733	894,339	914,365	909,392	905,556	875,422	845,265	790,231
Annual electricity consumption with typical size grid-connected PV systems	-	300,896	301,079	300,830	299,018	298,985	284,052	292,264	280,871	300,896	295,924	292,088	261,954	231,797	176,763
% Annual electricity reduction compared with ZEBs	-	0%	0%	0%	2%	2%	14%	7%	16%	0%	4%	7%	31%	56%	100%
Peak load (kW)	528.4	399.0	398.9	399.0	399.2	399.2	391.0	394.1	366.3	399.0	398.9	403.5	382.0	370.2	331.4
Peak load with PV systems installed	-	321.2	321.4	321.1	318.6	318.7	319.7	308.9	305.7	321.2	322.5	310.1	306.0	292.1	256.2
% Peak load reduction compared with ZEBs	-	2%	2%	2%	6%	6%	4%	20%	25%	2%	0%	19%	25%	46%	100%
Excess PV output and building power load met															
Electricity bought from grid (kWh)	739,435	520,821	520,863	520,753	519,488	519,364	510,259	513,536	505,799	520,821	517,191	514,306	492,403	470,972	435,895
Load met by PV output (kWh)	-	393,544	393,685	393,545	392,998	393,089	387,261	392,197	388,540	393,544	392,200	391,250	383,019	374,293	354,336
% Load met compared to total demand	0%	43%	43%	43%	43%	43%	43%	43%	43%	43%	43%	43%	44%	44%	45%
% Percentage load met by PV output compared with ZEBs	-	0%	0%	0%	2%	2%	6%	15%	22%	0%	5%	9%	40%	69%	100%
Excess electricity sold to grid (kWh)	-	219,924	219,783	219,923	220,470	220,379	226,207	221,271	224,928	219,924	221,268	222,218	230,449	239,175	259,132
% Excess electricity reduction compared with ZEBs	-	100%	100%	100%	98%	98%	84%	96%	87%	100%	96%	94%	73%	51%	0%
Economic analysis															
Annual electricity cost (Normal rate)	-	$ -	$ 20,082	$ 20,065	$ 19,944	$ 19,942	$ 18,946	$ 19,494	$ 18,734	$ 20,070	$ 19,738	$ 19,482	$ 17,472	$ 15,461	$ 11,790
Annual gas cost	-	$ -	$ 7,323	$ 7,323	$ 7,521	$ 7,412	$ 7,481	$ 6,703	$ 7,431	$ 6,429	$ 7,166	$ 6,919	$ 7,315	$ 7,360	$ 5,875
Total annual energy cost	-	$ -	$ 27,405	$ 27,388	$ 27,466	$ 27,354	$ 26,428	$ 26,197	$ 26,165	$ 26,498	$ 26,904	$ 26,401	$ 24,787	$ 22,821	$ 17,665
% Energy cost saving (Normal rate)	-	-	60%	60%	60%	60%	61%	62%	62%	61%	61%	61%	64%	67%	74%
$ Incremental investment from ASHRAE compliant building	-	-	$ 3,637,993	$ 3,654,944	$ 3,596,840	$ 3,889,777	$ 3,629,120	$ 3,800,251	$ 3,520,079	$ 3,509,800	$ 3,500,000	$ 3,500,000	$ 3,640,000	$ 3,513,389	$ 4,073,045
% Investment cost reduction compared with the highest invesment strategy	-	-	76%	73%	83%	32%	77%	48%	96%	98%	100%	100%	76%	98%	0%
Payback period (Year)	-	-	89	89	88	95	86	90	83	84	84	83	83	77	80
% Payback period reduction compared with the longest payback period strategy	-	-	34%	32%	39%	0%	47%	27%	65%	62%	59%	65%	64%	100%	82%
Emission															
Site emission (Ton CO2e)	-	246.56	246.43	246.24	245.36	245.07	233.92	238.21	231.39	244.07	242.13	238.61	216.76	194.01	148.60
% Site emission (Ton CO2e) reduction compared with ZEBs	-	0%	0%	0%	1%	1%	13%	8%	15%	2%	4%	8%	30%	54%	100%
Source emission (Ton CO2e)	-	787.67	787.85	787.21	783.13	782.75	744.84	763.68	736.60	784.95	774.27	763.81	688.03	611.23	466.82
% Reduction compared with existing buildings	-	13%	13%	13%	14%	14%	18%	16%	19%	14%	15%	16%	24%	33%	49%

Table 64. Performances of energy efficiency design strategies and grid-connected PV systems implemented in factory buildings in Duluth.

Metrices	Existing	ASHRAE	Wall insulation	Roof insulation	Glazing	Wall, roof, glazing	Daylighting	Thermal mass	Cooling	Heating	Desk temp. reset	Thermostat setting	High efficiency appliance	Lighting power density	Zero energy building
Electricity consumption															
Annual electricity consumption (kWh)	1,106,314	869,067	869,281	869,022	867,934	868,127	853,887	864,954	859,461	869,067	860,894	865,063	832,273	803,600	762,223
Annual electricity consumption with typical size grid-connected PV systems	-	258,990	259,204	258,946	257,857	258,051	243,810	254,877	249,384	258,990	250,817	254,987	222,196	193,523	152,147
% Annual electricity reduction compared with ZEBs	-	0%	0%	0%	1%	1%	14%	4%	9%	0%	8%	4%	35%	61%	100%
Peak load (kW)	493.9	387.4	386.6	387.1	383.9	382.9	376.3	372.7	356.6	387.4	385.1	379.2	371.9	358.6	309.0
Peak load with PV systems installed	-	285.7	284.6	285.4	281.2	280.2	279.9	272.1	265.4	285.7	284.2	275.3	270.1	255.9	235.7
% Peak load reduction compared with ZEBs	-	0%	2%	1%	9%	11%	12%	27%	41%	0%	3%	21%	31%	60%	100%
Excess PV output and building power load met															
Electricity bought from grid (kWh)	693,161	490,783	490,921	490,748	489,942	490,076	481,870	487,553	484,425	490,783	485,807	487,813	464,858	444,821	419,669
Load met by PV output (kWh)	-	378,284	378,360	378,274	377,991	378,052	372,017	377,401	375,036	378,284	375,087	377,251	367,414	358,779	342,555
% Load met compared to total demand	0%	44%	44%	44%	44%	44%	44%	44%	44%	44%	44%	44%	44%	45%	45%
% Percentage load met by PV output compared with ZEBs	-	0%	0%	0%	2%	2%	3%	8%	8%	0%	3%	6%	44%	79%	100%
Excess electricity sold to grid (kWh)	-	231,793	231,717	231,803	232,085	232,025	238,060	232,676	235,041	231,793	234,990	232,826	242,662	251,298	267,522
% Excess electricity reduction compared with ZEBs	-	100%	100%	100%	99%	99%	82%	97%	91%	100%	91%	97%	69%	45%	0%
Economic analysis															
Annual electricity cost (Normal rate)	-	$ -	$ 17,289	$ 17,272	$ 17,199	$ 17,212	$ 16,262	$ 17,000	$ 16,634	$ 17,275	$ 16,730	$ 17,008	$ 14,820	$ 12,908	$ 10,148
Annual gas cost	-	$ -	$ 8,901	$ 8,901	$ 9,150	$ 8,978	$ 9,074	$ 8,364	$ 9,012	$ 7,783	$ 8,808	$ 8,464	$ 8,952	$ 9,072	$ 7,255
Total annual energy cost	-	$ -	$ 26,190	$ 26,173	$ 26,349	$ 26,190	$ 25,336	$ 25,364	$ 25,646	$ 25,058	$ 25,537	$ 25,471	$ 23,773	$ 21,980	$ 17,403
% Energy cost saving (Normal rate)	-	-	61%	61%	61%	61%	62%	62%	62%	63%	62%	62%	65%	67%	74%
$ Incremental investment from ASHRAE compliant building	-	-	$ 3,637,993	$ 3,654,944	$ 3,596,840	$ 3,889,777	$ 3,629,120	$ 3,800,251	$ 3,519,527	$ 3,512,150	$ 3,500,000	$ 3,500,000	$ 3,640,000	$ 3,513,389	$ 4,074,843
% Investment cost reduction compared with the highest invesment strategy	-	-	76%	73%	83%	32%	78%	48%	97%	98%	100%	100%	76%	98%	0%
Payback period (Year)	-	-	89	90	89	95	87	91	85	84	84	84	84	78	82
% Payback period reduction compared with the longest payback period strategy	-	-	36%	34%	40%	0%	48%	23%	59%	67%	63%	64%	64%	100%	76%
Emission															
Site emission (Ton CO2e)	-	218.73	218.62	218.42	218.22	217.93	207.38	214.00	211.45	215.68	212.03	214.33	190.69	169.26	133.37
% Site emission (Ton CO2e) reduction compared with ZEBs	-	0%	0%	0%	0%	1%	13%	5%	8%	3%	8%	5%	33%	58%	100%
Source emission (Ton CO2e)	-	685.08	685.32	684.66	682.56	682.59	646.53	672.82	660.58	681.74	663.68	673.38	591.07	518.26	407.78
% Reduction compared with existing buildings	-	21%	21%	21%	21%	21%	26%	23%	24%	22%	24%	22%	32%	40%	53%

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