MODELING CARBON DIOXIDE EMISSIONS REDUCTIONS FOR THREE COMMERCIAL REFERENCE BUILDINGS IN SALT LAKE CITY

by

Stephen M. Lucich

A thesis submitted to the faculty of
The University of Utah
in partial fulfillment of the requirements for the degree of

Master of Science

Department of Mechanical Engineering

The University of Utah

May 2015

The University of Utah Graduate School

STATEMENT OF THESIS APPROVAL

The thesis of **Stephen M. Lucich**

has been approved by the following supervisory committee members:

Amanda Smith, Chair **3/11/2015** Date Approved

Kent Udell, Member **3/11/2015** Date Approved

Fernando Guevara Vasquez, Member **3/11/2015** Date Approved

and by **Tim Ameel**, Chair/Dean of

the Department/College/School of **Mechanical Engineering**

and by David B. Kieda, Dean of The Graduate School.

ABSTRACT

In the United States, the buildings sector is responsible for approximately 40% of the national carbon dioxide (CO_2) emissions. CO_2 is created during the generation of heat and electricity, and has been linked to climate change, acid rain, a variety of health threats, surface water depletion, and the destruction of natural habitats. Building energy modeling is a powerful educational tool that building owners, architects, engineers, city planners, and policy makers can use to make informed decisions. The aim of this thesis is to simulate the reduction in CO_2 emissions that may be achieved for three commercial buildings located in Salt Lake City, UT. The following two questions were used to guide this process:

1. How much can a building's annual CO_2 emissions be reduced through a specific energy efficiency upgrade or policy?
2. How much can a building's annual CO_2 emissions be reduced through the addition of a photovoltaic (PV) array? How large should the array be?

Building energy simulations were performed with the Department of Energys EnergyPlus software, commercial reference building models, and TMY3 weather data. The chosen models were a medium office building, a primary school, and a supermarket. Baseline energy consumption data were simulated for each model in order to identify changes that would have a meaningful impact. Modifications to the buildings construction and operation were considered before a PV array was incorporated. These modifications include (1) an improved building envelope, (2) reduced lighting intensity, and (3) modified HVAC temperature set points. The PV array sizing was optimized using a demand matching approach based on the method of least squares. The arrays tilt angle was optimized using the golden section search algorithm. Combined, energy efficiency upgrades and the PV array reduced building CO_2 emissions by 58.6, 54.0, and 52.2% for the medium office, primary school, and supermarket, respectively. However, for these models, it was determined that the addition of a PV array is not feasible from a purely economic viewpoint. Several avenues for expansion of this research are presented in Chapter 5.

"God Bless America. Let's save some of it!"

– Edward Abbey

CONTENTS

ABSTRACT . . . . . **iii**

LIST OF FIGURES . . . . . **vii**

LIST OF TABLES . . . . . **ix**

ABBREVIATIONS AND SYMBOLS . . . . . **x**

ACKNOWLEDGMENTS . . . . . **xii**

CHAPTERS

1. INTRODUCTION **1**

2. MODELING BUILDING CO_2 EMISSIONS **4**

2.1 EnergyPlus 4
2.2 Energy Efficiency Upgrades and Conservation Policy 7
2.3 On-Site Photovoltaic Generation and Optimal Sizing 8
2.4 Simulating Carbon Dioxide Emissions Reductions for Salt Lake City, UT . . . 10

3. SIMULATING ENERGY EFFICIENCY UPGRADES AND CONSERVATION POLICY **16**

3.1 Commercial Model Baseline Data 17
3.1.1 Medium Office Building 18
3.1.2 Primary School 19
3.1.3 Supermarket 19
3.2 Energy Efficient Modifications 20
3.2.1 Lighting Intensity 20
3.2.2 Building Envelope 21
3.2.3 Temperature Setpoints 22
3.2.4 Model Implementation 22
3.3 Results 23
3.4 Discussion 23
3.5 Conclusions and Future Work 25

4. OPTIMAL PHOTOVOLTAIC SIZING **42**

4.1 Demand Matching Optimization 42
4.2 PV Array Tilt Angle Optimization 44
4.3 Sizing Parameters 44
4.4 Results 45
4.5 Discussion 46
4.6 Conclusions and Future Work 48

4. OPTIMAL PHOTOVOLTAIC SIZING **42**
4.1 Demand Matching Optimization 42
4.2 PV Array Tilt Angle Optimization 44
4.3 Sizing Parameters 44
4.4 Results 45
4.5 Discussion 46
4.6 Conclusions and Future Work 48

5. CONCLUSIONS AND FUTURE WORK **56**

APPENDICES

A. MODEL FLOOR PLANS **59**

B. MATLAB CODE **62**

REFERENCES **66**

LIST OF FIGURES

1.1 Energy consumption breakdown by sector in the United States 3
1.2 CO_2 emissions breakdown by sector in the United States 3
2.1 Electricity conversion methods used in Utah 12
2.2 Electricity conversion methods used in Idaho 12
2.3 PV resource distribution in the United States 14
2.4 Peak shaving example 15
3.1 Medium office commercial reference model 27
3.2 Baseline energy consumption breakdown for the medium office 27
3.3 Primary school commercial reference model 28
3.4 Baseline energy consumption breakdown for the primary school 28
3.5 Supermarket commercial reference model 29
3.6 Baseline energy consumption breakdown for the supermarket 29
3.7 EnergyPlus lighting intensity object 31
3.8 EnergyPlus window object 32
3.9 EnergyPlus material object 33
3.10 EnergyPlus temperature setpoint schedule 34
3.11 Medium office lighting intensity reduction 36
3.12 Medium office window construction 36
3.13 Medium office wall insulation 37
3.14 Medium office temperature setpoint adjustment 37
3.15 Primary school lighting intensity reduction 38
3.16 Primary school window construction 38
3.17 Primary school wall insulation 39
3.18 Primary school temperature setpoint adjustment 39
3.19 Supermarket lighting intensity reduction 40
3.20 Supermarket window construction 40
3.21 Supermarket wall insulation 41
3.22 Supermarket temperature setpoint adjustment 41

4.1 Solar radiation incident on an angled PV array 49
4.2 Trial and error technique results 49
4.3 Demand matching data for the improved medium office building summed by week 50
4.4 Hourly demand matching data for the improved medium office building 51
4.5 PV array area vs. annual cost and CO_2 emissions for the medium office 53
4.6 PV array area vs. annual cost and CO_2 emissions for the primary school 54
4.7 PV array area vs. annual cost and CO_2 emissions for the supermarket 55
A.1 Medium office commercial reference model floor plan 59
A.2 Primary school commercial reference model floor plan 60
A.3 Supermarket commercial reference model floor plan 61

LIST OF TABLES

2.1 ASHRAE's published AEDGs for a 30% and 50% reduction in building energy consumption . . . 13

3.1 HDD and CDD for a selection of cities in the U.S. . . . 26

3.2 CO_2 emission conversion factors . . . 26

3.3 Commercial model baseline performance data . . . 30

3.4 Results summary for CO_2 emissions reductions . . . 35

4.1 PV array sizing parameters . . . 50

4.2 PV array sizing summary . . . 52

4.3 Cost and emissions results summary with installed PV . . . 52

5.1 Summary of CO_2 reductions . . . 58

ABBREVIATIONS AND SYMBOLS

Abbreviations

AEDG	Advanced Energy Design Guide
ASHRAE	American Society of Heating, Refrigeration, and Air Conditioning Engineers
BLAST	Building Loads Analysis and System Thermodynamics
CBECS	Commercial building energy consumption survey
C	Cooling
CDD	Cooling degree day
COP	Coefficient of performance
CO_2	Carbon dioxide
DOE	Department of Energy
EIA	Energy Information Administration
EH	Electric heating
EROI	Energy return on investment
GHG	Greenhouse gas
HDD	Heating degree day
HVAC	Heating, ventilation, and air conditioning
L	Lighting
LBNL	Lawrence Berkeley National Laboratory
LCOE	Levelized cost of energy
LED	Light-emitting diode
MPPT	Maximum power point tracking
NREL	National Renewable Energy Laboratory
NGH	Natural gas heating
P	Pumps and fans
PNNL	Pacific Northwest National Laboratory
PSO	Particle Swarm Optimization
PV	Photovoltaic
R	Refrigeration
SAV	Surface area to volume ratio
SHGC	Solar heat gain coefficient
TMY3	Typical meteorological year 3
V	Ventilation
WWR	Window to wall area ratio

Symbols

Variable	Units	Description
A_S	[m^2]	Surface area of the PV array
C_G	[$]	Grid electricity rate
C_S	[$	Surplus electricity rate
E_d	[W]	Average building power demand over time step
E_{PV}	[W]	Average power produced by PV array over time step
EF_G	–	Regional emissions factor for simulation location
EF_{min}	–	Smallest regional emissions factor in the United States
I_{GI}	[W/m^2]	Incident solar radiation (direct and diffuse)
I_{GT}	[W/m^2]	Total solar radiation (direct and diffuse)
n	–	Number of time steps
SS	–	Site to source electricity conversion factor
x	–	Surplus penalty
y	–	Emissions penalty
α	degrees	Solar altitude angle
β	degrees	PV array angle
η_{IN}	–	Inverter efficiency
η_{PV}	–	PV efficiency

ACKNOWLEDGMENTS

Quite a few people contributed to the development of this thesis into a coherent and organized work. I'd like to thank my advisory committee, especially Amanda Smith, for their patience and profound guidance during this process. You have inspired in me a new confidence with which I can analyze and creatively solve difficult problems. I would also like to thank Carlo, Aowabin, and Thomas for their support in both coursework and research.

Additionally, I would like to thank the University of Utah's Global Change and Sustainability Center for providing travel funding to the 2014 ASME International Conference on Energy Sustainability in Boston, MA. This was a wonderful opportunity to practice presenting my work to a technical audience, as well as learn about state-of-the-art research in sustainability.

I'd like to thank Bart Raeymaekers, Amanda Smith, and Kent Udell for trusting in me and providing the opportunity to TA or grade for their classes. Teaching and working with students was a great opportunity to develop speaking, teaching, and conflict resolution skills.

I'd also like to thank the University of Utah's Outdoor Adventures Program for bringing me into the volunteer trip leader program. Through these outdoor experiences, I made many new friends who encouraged me to be goofy and promoted a balanced and healthy lifestyle.

And lastly, I'd like to thank my parents for their continued support and advice during this occasionally stressful process.

CHAPTER 1

INTRODUCTION

In 2010, the United States was the world's second largest consumer of energy at 97.8 quads ($1.055 * 10^{18}$ joules) and produced approximately 5644 million metric tons of carbon dioxide (CO_2). The buildings sector is responsible for 41% of the total primary energy consumption and 40% of the national CO_2 emissions [1][2]. This is more than both the transportation sector, and the industrial sector (Figures 1.1 and 1.2).

Of the energy supplied to buildings, approximately 75% is supplied by the combustion of fossil fuels, 16% is generated at nuclear power plants, and 9% is supplied by renewable generation [1]. CO_2 and other greenhouse gases (GHG) are a product of the combustion of fossil fuels [3][4]. Seventy percent of building energy is consumed through heating, cooling, and lighting processes [1]. The aim of this thesis is to simulate the reduction in CO_2 emissions that may be achieved for three commercial buildings located in Salt Lake City, UT.

Generating electricity using fossil fuels has been linked to climate change, acid rain, a variety of health threats, surface water depletion, and the destruction of natural habitats [4][5]. On the other hand, the generation of sustainable energy has its own disadvantages, including land use, destruction of natural habitats, and GHG emissions and pollution during construction or manufacturing [4, 6, 7]. Improved energy efficiency is frequently cited as the most cost-effective method to reduce building energy consumption, and consequently CO_2 emissions [8, 9, 10, 11]. However, the long-term effects of energy efficiency are not certain. It is possible that increased energy efficiency could lead to increased energy use globally as new technology becomes more readily available in developing nations [12].

The issue of climate change is a complex problem that cannot be solved by a single solution. Environmental problems require a balance of technological, behavioral, and structural solutions [13]. Solar photovoltaics (PV) and LED lighting are two examples of a technological solution. Behavioral solutions are brought about through increased levels of education and feedback to the consumer, and structural solutions involve the circumstances that influence an individual's decision-making process. For example, these circumstances could include energy prices, demand response pricing, carbon taxes, or public policy.

Building energy modeling software is a powerful educational tool that building owners, architects, engineers, city planners, and policy makers can use to make informed decisions. The research contained in this thesis focused primarily on the following questions for three model buildings located in Salt Lake City.

1. How much can a building's annual CO_2 emissions be reduced through a specific energy efficiency upgrade or policy?

2. How much can a building's annual CO_2 emissions be reduced through the addition of a PV array? How large should the array be?

Building energy simulations were performed with the Department of Energy's (DOE) EnergyPlus software [14], commercial reference building models [15], and typical meteorological year 3 (TMY3) weather data [16]. The chosen models were a medium office building, a primary school, and a supermarket. Baseline energy consumption data were simulated for each model in order to identify changes that would have a meaningful impact. Modifications to the building's construction and operation were considered before a PV array was incorporated. These modifications include (1) an improved building envelope, (2) reduced lighting intensity, and (3) modified HVAC temperature set points. The PV array was optimally sized for the baseline model, as well as a model including all of the selected modifications.

This thesis is divided into five chapters. Chapter 2 provides detailed background information and a review of relevant scientific literature. Chapter 3 focuses on energy efficiency upgrades and operational policy, while Chapter 4 proposes an optimal sizing technique for a solar PV array. Chapters 3 and 4 contain individual results and discussion sections that are summarized in Chapter 5. Chapter 5 also presents ideas for the continuation of this research.

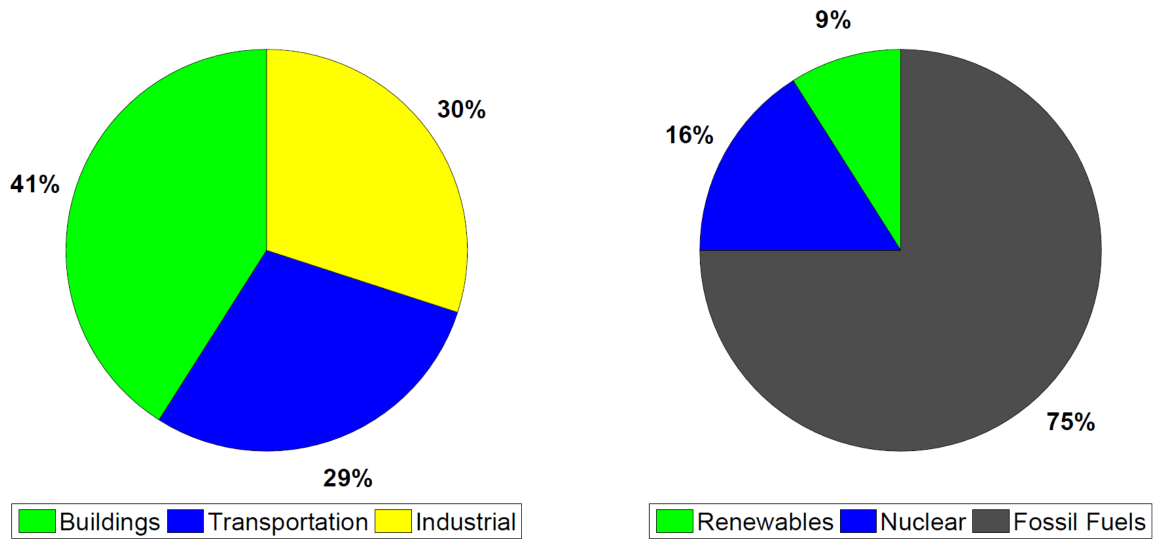

Figure 1.1. Energy consumption breakdown by sector in the United States [1]

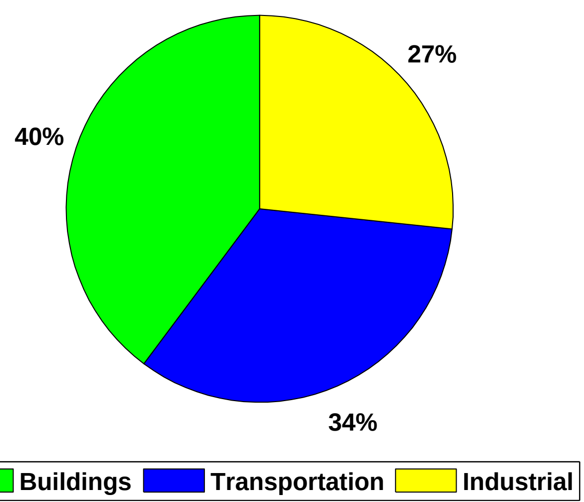

Figure 1.2. CO_2 emissions breakdown by sector in the United States [1][2]

CHAPTER 2

MODELING BUILDING CO_2 EMISSIONS

Building energy modeling is a powerful educational tool than can be used to quantify a building's energy consumption, as well as the resulting GHG emissions. A building's energy consumption depends on its location, size, purpose, construction, and operation. GHGs, including CO_2, are produced during the conversion of electricity and heat from primary energy sources. The magnitude of CO_2 production depends on the location and the method of conversion. For example, Figures 2.1 and 2.2 break down the power generation fuel sources for Utah and Idaho, respectively [17]. Utah relies primarily on coal power plants, while Idaho relies primarily on hydroelectric power plants.

Compared against coal power plants, hydroelectric plants produce very little CO_2 during their lifetime [18][19]. In 2011, Utah was responsible for approximately 63.9 million metric tons of CO_2 (22.7 metric tons per capita), while Idaho was responsible for 15.5 million metric tons of CO_2 (9.8 metric tons per capita) [20]. These values account for the buildings, industrial, and transportation sectors. Furthermore, a distinction must be made between site and source energy [21] when comparing energy consumption in the building sector. Site energy is measured at the location of consumption and is useful for building efficiency analysis. However, site energy does not account for inefficiencies during extraction, conversion, or transmission. Combined with building modeling software, source energy and emissions conversion factors allow a detailed comparison of the effects of building energy consumption depending on location, size, purpose, construction, and operation.

2.1 EnergyPlus

Americans became interested in tracking and modeling building energy consumption following the energy crisis of the early 1970s [22][23]. The U.S. DOE recognized that buildings consumed a significant portion of the total energy demand and wanted to develop tools to promote energy efficiency. Consequently, the BLAST (Building Loads Analysis and System Thermodynamics) and DOE-2 programs were developed. EnergyPlus, the

DOE's modern simulation software, is a direct descendant of the BLAST and DOE-2 programs. Researchers, engineers, and architects rely on EnergyPlus to perform building load calculations, size HVAC systems, perform energy and thermal analyses, and optimize building energy systems. Some of the major features of EnergyPlus are [22][24]:

- Integrated, simultaneous solutions
- Heat balance-based solution
- Transient heat conduction
- Advanced fenestration simulation
- Daylighting controls
- Improved ground heat transfer models
- Sub-hourly time steps
- ASCII text-based input, output, and weather files

At its core, EnergyPlus determines the heating and cooling loads required to sustain thermal equilibrium for a given building model and weather file. The research detailed in this thesis relies on TMY3 weather files and commercial reference building models. A TMY3 weather file is a data set of meteorological information that represents typical weather conditions over a 30-year period. TMY3 data were collected between 1976 and 2005 for 1020 locations in the United States and its territories [25].

The commercial reference models were constructed around data collected in the U.S. Energy Information Administration's (EIA) commercial building energy consumption survey (CBECS) [26][27]. The first CBECS survey was conducted in 1979; the tenth survey was completed in 2013. Data were collected from two sources: a building respondent and the energy supplier. CBECS data are composed of energy use data, as well as specific building characteristics. If over half of a building's floorspace is not used for residential, industrial, or agricultural purposes, then a building is classified as commercial. The commercial reference model package was developed under the DOE building technologies program and the following research laboratories: the National Renewable Energy Laboratory (NREL), the Pacific Northwest National Laboratory (PNNL), and Lawrence Berkeley National Laboratory (LBNL). Building models were based on the most popular building types of the U.S. building stock and are estimated to represent two-thirds of the national building stock. Some of the remaining one-third are similar to one or more of the commercial models, but have a different purpose [26]. The user may choose between three construction dates for each model: new construction, post-1980 construction, and pre-1980 construction. The main difference between these three dates are the values used to model insulation, lighting, and HVAC equipment. The layout of the building models is the same for each construction period. Like EnergyPlus and the TMY3 data, the commercial reference models were designed primarily for researchers, engineers, and architects. The reference models are a baseline to measure the impact of various building efficiency measures, optimize design parameters, analyze building controls, develop new building standards, etc. [26, 28, 29].

EnergyPlus is focused on whole-building energy simulation that encompasses all aspects of building energy use, including thermal and visual comfort. Additional features are accompanied with increased software complexity. As a result, it may be difficult to validate the accuracy of simulation results. The American Society of Heating, Refrigeration, and Air Conditioning Engineer's (ASHRAE) Standard 140 was the first codified method to test, verify, and validate results [30]. Simulation accuracy is evaluated under the following three conditions [31]:

- Empirical Validation - Model results are compared against actual building data or data collected in laboratory experiments.
- Analytical Verification - Model results are compared against results from an analytical method or a numerical method for isolated heat transfer.
- Comparative Testing - Model results are compared with results from other models or other software.

There are advantages and disadvantages associated with each method. For example, analytical verification is often inexpensive and will conform to mathematical law, but just because a model is mathematically correct does not mean that it is the appropriate model to simulate a physical phenomenon. On the other hand, empirical validation confirms a model's application, but can be expensive, time consuming, and prone to human error and instrument uncertainty. Empirical validation conforms to physical laws. Comparative testing is quick, inexpensive, and great for diagnostic comparison, but does not conform to any mathematical or physical law. Standard 140 is based on a procedure developed by NREL and is subdivided into six categories [30][32].

1. Comparative testing - building envelope

2. Comparative testing - mechanical equipment and on-site energy generation
3. Analytical verification - building envelope
4. Analytical verification - mechanical equipment and on-site energy generation
5. Empirical validation - building envelope
6. Empirical validation - mechanical equipment and on-site energy generation

Currently, Standard 140 focuses on categories one and four; however, expansion is planned once additional methods are developed.

2.2 Energy Efficiency Upgrades and Conservation Policy

Increasing energy efficiency is frequently cited as the most cost-effective method to reduce building energy consumption, and consequently CO_2 emissions [8, 9, 10, 11]. A report by the National Academy of Sciences and the National Academy of Engineering estimates that energy efficiency has the potential to reduce American energy consumption up to 25-30% by the year 2030. This estimate accounts for an increase in demand due to population and building growth [9].

Building energy efficiency may be achieved through a variety of means including: energy-efficient lighting, increased insulation, and intelligent building controls. ASHRAE publishes Advanced Energy Design Guides (AEDG) for building owners to achieve 30 or 50% energy savings over the minimum building code (ASHRAE Standard 90.1) [33]. The current publications include the following building types (Table 2.1) and serve as a starting point for those interested in increasing energy efficiency or reducing GHG emissions for a specific climate zone. The prescriptive recommendations provided may not be applicable to every specific building and should be evaluated on a case-by-case basis.

Behavioral change may be initiated through direct or indirect feedback to the building occupant. An example of indirect feedback would be through utility billing [34]. The majority of occupants recognize the importance of energy conservation, but they cannot relate their own personal behavior to energy consumption [35]. While the production of electricity is often very visible, it is also localized [34]. In other words, people who live or work near a power plant, oil field, or other energy development are exposed to the effects of energy consumption more often than those living in large cities. The consumption of energy is largely invisible to those living far from its production. Feedback allows the occupant to develop the ability to recognize energy conservation potential. For example, the study by

Petersen et al. observed a reduction in energy consumption of 32% in a college dormitory when residents were exposed to real-time feedback. This reduction increased to 55% when the resolution of feedback increased and was made available through a web browser [5]. As smart power meters continue to grow more popular, another option is to provide building occupants with detailed energy information through their phone or other mobile device [36].

2.3 On-Site Photovoltaic Generation and Optimal Sizing

Sustainable energy generation technology can be incorporated to further reduce grid consumption and offset GHG emissions. In modern society, solar energy is commonly collected in one of the following three forms: (1) PV, (2) active solar thermal, (3) passive solar thermal [4][37]. This research will focus on the addition of a PV array because solar radiation is abundant in Salt Lake City, UT (Figure 2.3) [4, 38, 39] and PV can be added to rooftops in urban locations.

PV panels directly convert sunlight into electric energy. They are durable, solid-state devices that require very little maintenance and an array can be scaled to provide output from microwatts to megawatts. When compared with conventional fossil fuel power production, PV technology offers many attractive environmental and socio-economic benefits, including a reduction in the production of greenhouse gas emissions, a reduction in power transmission lines, improvements in water quality, regional or national energy independence and security, job creation, and rural electrification in developing areas. While PV technology is commonly accepted as the most environmentally friendly solar option, it is not entirely free from negative side effects. For example, PV technology can significantly impact the natural ecosystems, change the local landscape, emit pollutants that contaminate soil and groundwater, deplete scarce natural resources, and release GHG emissions during the manufacturing process [7]. A report by Fthenakis designates the Southwestern U.S. as an ideal candidate for large-scale solar PV applications due to its open expanses of land, high levels of insolation, and a rapidly increasing demand for water [40]. Coal, natural gas, and nuclear power plants are estimated to use thousands of liters of water per megawatt hour during electricity production compared to four liters of water per megawatt hour used for cleaning solar PV panels.

Many economic tools exist to evaluate solar energy. One option, the simple payback period, divides the cost of the system by the amount saved annually. This approach is useful as a screening tool for the early design stage, but a more detailed analysis is often required. Kreith provides a detailed breakdown using the present worth, inflation, fuel pricing, and other lifecycle and societal costs [41]. When performing an economic analysis, it is important to include as many costs as are currently known. Solar systems often include the following:

- PV panels – cost and delivery
- Installation and infrastructure costs
- Value of floor space or land required
- Thermal and electric storage
- Maintenance, repair, and replacement
- Taxes and insurance

Two additional metrics that are useful for evaluating solar energy technology are the levelized cost of energy (LCOE) and the energy return on investment (EROI). Similar to the standard economic methods mentioned above, these metrics are useful for evaluating systems; however, instead of making broad investment comparisons, they are useful when comparing energy generation techniques. The LCOE is defined as: "a cost that, if assigned to every unit of energy production (or saved) by the system over the analysis period, will equal the total lifecycle costs when discounted back to the base year" [37]. However, predicting the lifetime productivity and costs associated with a PV system is quite challenging. Several assumptions are made beyond simply using the vendor's reported conversion efficiency and a location's average insolation value [42][43]. The EROI seeks to relate the total electricity generated during a system's lifecycle to the total amount of energy required to build, transport, operate, and demolish the system [37].

One of the major limitations of PV is that it does not always coincide with electricity demand. For residential buildings, there is often a mismatch between PV availability, building demand, and electricity price [44]. One possible solution to this problem is to incorporate an energy storage system to preserve energy for later use. As the peak demand to average hourly demand ratio continues to rise throughout the United States, additional strain is placed on the generation capacity of energy utilities [45]. Baseload electricity service is generally provided by large coal power plants, nuclear power plants, or large hydroelectric projects that cannot scale production to match demand quickly [46]. Immediate energy demand is frequently met using smaller scale coal and natural gas units. Energy storage may be incorporated into a distributed energy generation system to assist in meeting immediate energy demand. This process is often referred to as peak shaving (Figure 2.4) [47]. However, a quick comparison between the average PV LCOE (0.14 [$/kWh] [48]) and the surplus rate (0.0277 [$/kWh] [49]) does not provide an economic incentive for peak shaving with PV.

Previous work reviewed by Salas et al. has focused on (1) defining a suitable array location, (2) determining the optimum tilt angle, and (3) maximizing PV output with variable solar irradiation using maximum power point tracking (MPPT) [50]. More specifically, Arun et al. developed optimal sizing methods for stand-alone residential PV-battery systems that focus on storing energy during daylight hours for use at night [51][52]. For a grid connected PV-battery system, electricity prices should also be considered. In this system, the batteries are charged while utility prices are low, and discharged while electricity prices are high [44]. Overall, there is a significant collection of research that focuses on techniques to optimize a PV array [53][54][55]. Additionally, Toledo et al. [56] compares the efficiency, capacity, and reliability of several energy storage methods and their usefulness when paired with PV. Erdinc and Uzungoglu [57] review many common mathematical techniques for system sizing including: genetic algorithms, particle swarm optimization (PSO), simulated annealing, ant colony algorithms, and artificial immune system algorithms to name a few. The majority of the methods described in these reviews are quite complicated. Khatib et al. state that "It is important to optimize the optimization method. In other words, the best optimization models must combine simple concepts with accurate results" [54]. Current research is also lacking detailed analysis that focuses on CO_2 emissions reductions for a specific location.

2.4 Simulating Carbon Dioxide Emissions Reductions for Salt Lake City, UT

There is a significant amount of literature related to energy efficiency, human behavior, energy conservation, and optimal sizing techniques for sustainable energy technology. However, there is very little information available on CO_2 emissions reductions resulting from changes to these elements. The aim of this thesis is to explore the reduction in CO_2 emissions that may be achieved for three commercial buildings located in Salt Lake City, UT. Total operation and capital costs were also considered, but from a secondary perspective as it is difficult to obtain accurate pricing information for commercial reference models. The chosen buildings are a medium sized office building, a primary school, and a supermarket. These buildings were chosen since each has a remarkably different purpose. Simulations were run using EnergyPlus with commercial reference models constructed after 1980, and TMY3 data. The effects of modifications to the building's construction and operational schedule were examined before site renewable energy was added. Baseline consumption data were simulated for each model in order to identify changes that would have a meaningful impact. Each modification was simulated separately before a combined simulation was run. Once the combined simulation was complete, the data were organized and a photovoltaic (PV) array was added to each building's roof. Results from each simulation were organized so that CO_2 emissions could be compared.

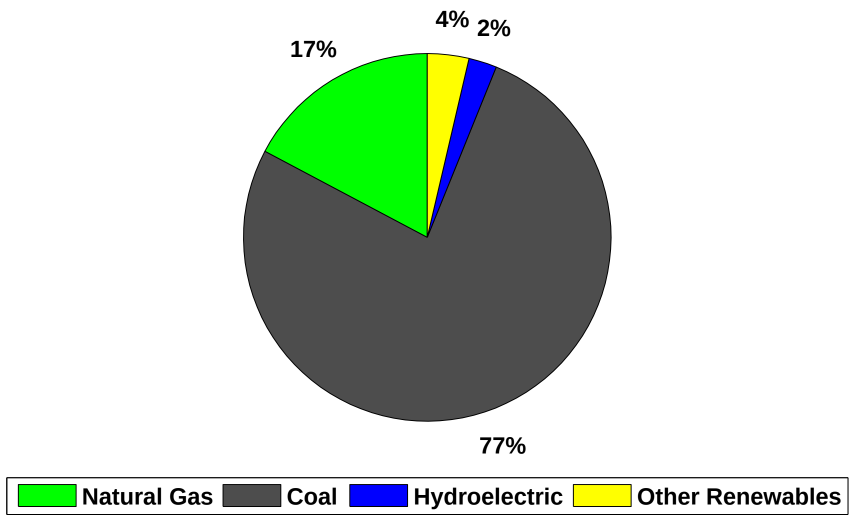

Figure 2.1. Electricity conversion methods used in Utah [17]

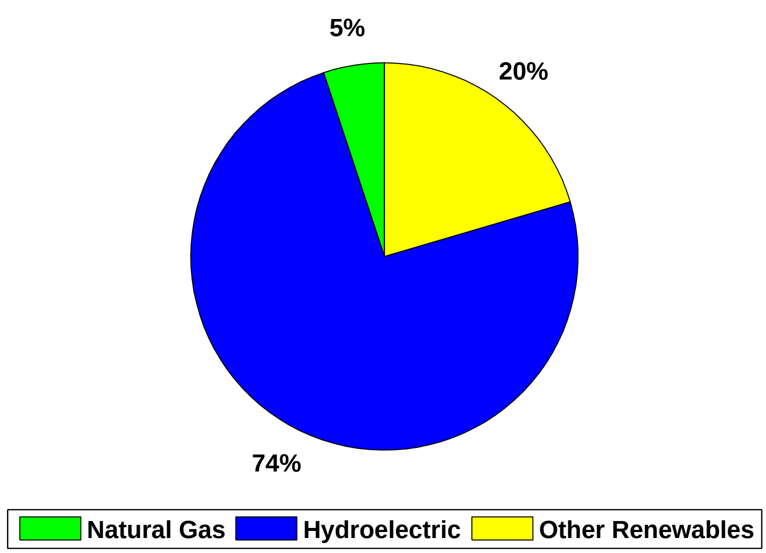

Figure 2.2. Electricity conversion methods used in Idaho [17]

Table 2.1. ASHRAE's published AEDGs for a 30% and 50% reduction in building energy consumption

30% Design Guides	**50% Design Guides**
Small Office Buildings	Small to Medium Office Buildings
Small Retail Buildings	Medium to Large Retail Buildings
Small Hospitals and Heathcare Facilities	Large Hospitals
K-12 School Buildings	K-12 School Buildings
Small Warehouses and Self-Storage Buildings	
Highway Lodging	

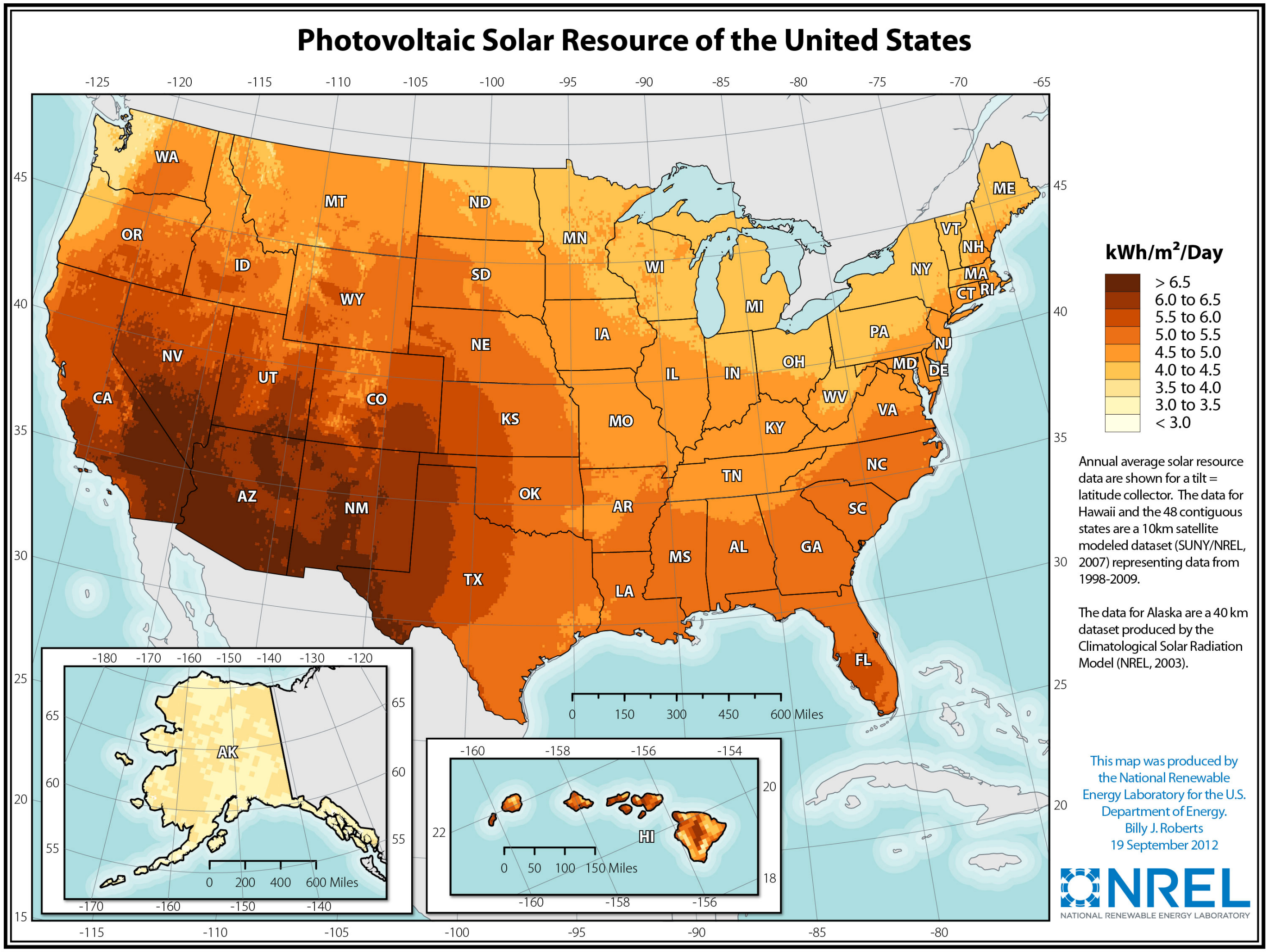

Figure 2.3. PV resource distribution in the United States [39]

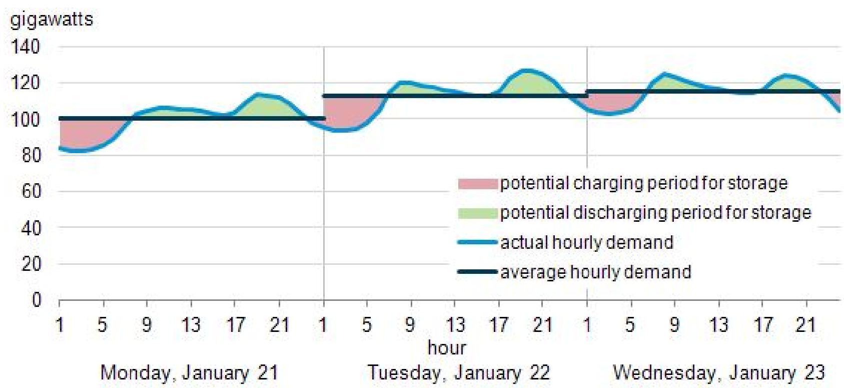

Figure 2.4. Peak shaving example [47]

CHAPTER 3

SIMULATING ENERGY EFFICIENCY UPGRADES AND CONSERVATION POLICY

During the design or renovation of a commercial building, the metrics included on an ASHRAE data sheet [32] as well as ASHRAE's AEDGs [33] are useful tools for performing a preliminary building analysis based on the climate of a specific location. Information on AEDGs was provided in Chapter 2, and will be expanded later in this chapter. An ASHRAE data sheet provides a summary of design conditions for a specific location. This includes monthly values for heating, humidification, cooling, dehumidification, extreme conditions, wind speed, precipitation, irradiance, and temperature.

For example, Salt Lake City experiences approximately 3059 °C (18.3 °C base) heating degree days (HDD) and 677 °C (18.3 °C base) cooling degree days (CDD) annually [32]. Comparing these values for HDD and CDD with other cities (Table 3.1), it is clear that Salt Lake City experiences a large heating load and a moderate cooling load.

From this information it is possible to conclude that a building in Salt Lake City would benefit from an improved envelope. Furthermore, the potential for daylighting and solar gains may be determined from HDD and CDD. A location with a large CDD and a small HDD likely receives more sunlight than an area with a large HDD and small CDD [33]. Salt Lake City's cooling load is large enough to indicate that daylighting may be beneficial, but care should taken not to increase the winter heating load when expanding the window area [33]. While useful early in the design process, this information is not as detailed as modern computer simulation software.

Traditionally, the design process for the construction or renovation of a commercial building abides by the following general structure:

1. Determine the building function, floor plan, aesthetics, and budget

2. Perform building loading calculations with specific building materials, and general weather data

3. Size building systems based on the loading calculations

4. Iterate the design in order to satisfy design constraints

Not only is this process time consuming and tedious, but it is very susceptible to human error. Multiple iterations aimed at determining the most efficient design could require hundreds, if not thousands of calculations. The DOE's EnergyPlus software [14] combined with TMY3 weather data [16] is a powerful and inexpensive tool for developers and building owners. EnergyPlus may be paired with the DOE's commercial reference model package to produce general results based on building type. Additional information on the structure and accuracy of EnergyPlus, as well as the development of the commercial reference models is included in Chapter 2. For this research, the site to source emission factors were assumed to be independent of location based on the data presented by Deru and Torcellini [21]. The site to source conversion was accounted for in the EnergyPlus simulation. Source energy was converted to CO_2 emissions using the conversion factors listed in Table 3.2 (Equation 3.1).

$$CO_2 = E_d * EF_G * SS \tag{3.1}$$

In the above equation, CO_2 represents the total emissions resulting from the purchase of electricity from the grid. E_d is the building's electricity demand, EF_G is the emissions conversion factor, and SS is the site to source conversion factor.

In this chapter, the simulation results for three commercial reference models are discussed. First, the baseline energy consumption is analyzed alongside general building information. The following energy efficiency modifications were identified: reduced lighting intensity, an improved thermal envelope, and altered temperature setpoints. Improvements to the thermal envelope include upgraded windows and insulation. Results from these simulation are presented in terms of energy consumption, as well as the reduction in CO_2 emissions possible. Simulation results are followed by a discussion of building improvements and the EnergyPlus software. All work presented in this chapter is a continuation of previous work [58].

3.1 Commercial Model Baseline Data

The three commercial reference models selected are a medium office building, a primary school, and a supermarket. These models are representative of buildings constructed sometime between 1980 and 2004. The baseline model does not contain state of the art technology and may not meet all current building codes. As a result, there is a great opportunity for significant improvement.

3.1.1 Medium Office Building

The medium office building model represents a three story building with 15 occupied zones and three unoccupied plenums (Figure 3.1). The plenum is located directly above each occupied level and contains HVAC equipment and ductwork. The medium office has a total floor area of 4982 square meters, a surface area to volume (SAV) ratio of 0.18, and a window to wall ratio (WWR) of 0.33. Both SAV and WWR are important indicators of heat transfer potential across exterior building surfaces. For example, a higher SAV indicates the building has a larger surface area exposed to the surrounding environment. Since windows generally have a lower thermal resistance than walls, a high WWR indicates large potential for heat transfer through the building's windows. The SAV is calculated using the surface area of the building's walls, roof, and total volume. WWR is calculated using the surface area of the building's windows and walls.

The medium office has a steel frame construction and is built upon a concrete slab foundation. More specifically, the exterior wall construction contains the following components: wood siding, steel frame with insulation, and 1/2 inch gypsum board. The interior walls consist of two, 1/2 inch gypsum boards and the floor is carpeted. All windows are continuous, and wrap around the building. The roof has an outer membrane, insulation, and metal decking. These values, as well as additional occupancy and energy consumption information are summarized in Table 3.3. A detailed floor plan is included in Appendix A.

In order to determine where to focus energy efficiency and conservation measures, a simulation was performed with the baseline model. The results of this simulation are shown in Figure 3.2. Lighting includes interior and exterior lighting and is responsible for over one-third of total consumption. Equipment includes items commonly found in an office, for example: computers, coffee machines, microwaves, printers, and miscellaneous plug loads. It does not include refrigeration or any component of the HVAC system. Similarly, cooling refers to space conditioning and does not include refrigeration. For the medium office model, it is clear that focus should be given to lighting, followed by electrical loads and space conditioning.

3.1.2 Primary School

The primary school model represents a one story building with 25 occupied zones (Figure 3.3). Unlike the medium office, it does not contain a plenum above the zones. The primary school does have a dedicated mechanical room for HVAC equipment and a drop down ceiling that contains ductwork. The total floor area is 6871 m^2 with an SAV of 0.34 and a WWR of 0.35. Construction materials are identical to those used in the medium office model. As a result, R-Values and U-Factors for the primary school's exterior envelope are identical to the medium office (Table 3.3).

Baseline energy consumption data for the primary school are shown in Figure 3.4. From the SAV and Figure 3.3, it is evident that the primary school is more spread out than the medium office. While the exposure of more surface area contributes to a higher percentage of energy for heating, it also increases the building's daylighting potential. Since the floor area is larger, it is expected that more energy will be consumed for space conditioning. The average lighting intensity and equipment intensity is also greater than those of the medium office building. Overall, the primary school consumes more energy than the medium office and produces a greater amount of CO_2 emissions. Attention should be given to lighting first, followed by space conditioning and electrical equipment.

3.1.3 Supermarket

The supermarket model represents a one story building with six occupied zones (Figure 3.5). Like the primary school, there is a drop down ceiling for ductwork, but HVAC equipment is located in each zone instead of a mechanical room. The total floor area is 4180 m^2 with an SAV of 0.23 and a WWR of 0.11.

The supermarket has concrete walls, as well as a concrete foundation. More specifically, the exterior wall construction contains the following components: 1 inch stucco siding, 8 inches of concrete, insulation, and 1/2 inch gypsum board. The interior walls and roof construction are identical to the medium office and primary school. Unlike the previous models, the supermarket contains only one window on the building's south face.

It is important to note that the insulation R-Value shown in Table 3.3 does not account for the exterior wall material of the model. In this case, there is a significant thermal mass outside of the insulation, which could contribute to a higher heating load. Additionally, a supermarket is full of refrigeration equipment. During winter, heat will constantly be lost to refrigeration units increasing both the refrigeration and heating load. The supermarket's maximum lighting load is smaller than the primary school's even though its average lighting intensity is greater. This could be attributed to some combination of the smaller floor area and a different operational schedule. Overall, the supermarket consumes the most energy through refrigeration, heating, and lighting (Figure 3.6).

3.2 Energy Efficient Modifications

ASHRAE's AEDGs provide a comprehensive review of building energy efficiency recommendations and practical information to consider during the design of a new building or renovation of an existing building. More specifically, these recommendations fall into the following categories: building envelope, daylighting, interior lighting, exterior lighting, plug loads, service water heating, HVAC systems and equipment, and quality assurance. After a thorough review of the design guides, lighting intensity, building envelope, and building temperature setpoints received the most focus. The aim of this section is to outline many of the recommendations provided in ASHRAE's AEDGs and justify the techniques chosen in this research [33].

3.2.1 Lighting Intensity

Lighting intensity refers to the amount of power consumed to provide light for a square meter of floor space in a building zone. In order to reduce a building's lighting intensity, a variety of techniques should be used together to achieve the best results. This includes technological improvements, daylighting, and adjustment of human behavior [33].

Unfortunately, daylighting is very dependent on the building's footprint and must be integrated early in the building's design phase. It is not an improvement that can be fully implemented during renovation. If daylighting is desired early in the design phase, the building's main face should be oriented within 15° of due south [33]. The building should also be clear of shade from other buildings or trees that may reduce the daylighting potential. There is a definite trade off between daylighting and the building's thermal envelope. As more building surface is exposed, there is a larger area over which heat transfer will occur. A high WWR indicates more window area which is also vulnerable to more heat transfer than walls. To maximize daylight potential, the building depth should be minimized to decrease the distance between exterior walls and occupied interior space. Courtyards can be used if the building lot is not very long. Light interior wall finishes will increase the reflectance of interior surfaces [33].

Automatic window shading or blind systems help reduce glare and solar heat gain. Automatic dimming can be used to reduce interior lights when daylighting is available, and motion sensors detect unoccupied zones and turn off their lights. Lighting efficiency is easily improved using T8 lamps with electronic ballast. Similar to daylighting, there are trade offs between many technological fixes and the building space conditioning demand. For example, more efficient lighting produces less heat and could increase the load on the building's HVAC system [33].

Educational programs to reduce demand are a commonly used and effective solution. Providing employees with energy consumption data and encouraging friendly competition or benefits is one approach. Care must be taken to incorporate a lighting system that meets occupant needs while simultaneously reducing consumption. For example, in select applications, restricting task lighting will contribute to reduced lighting intensity, but there may be special needs that override this policy [33].

3.2.2 Building Envelope

The building envelope refers to building surfaces that separate the built environment from the surroundings and includes: exterior walls, insulation, windows, doors, vestibules, etc. Improving the quality of the building's insulation by increasing the construction's thermal resistance is a good starting point, but care must be taken to include all surfaces in order to avoid thermal bridging. Thermal bridging occurs when two surfaces with significantly different values of thermal resistance are placed in parallel to each other. For example, a window's frame is often a weak point in building's envelope. Similar to electrons in a circuit, heat travels fastest through the path of least resistance. If a metal framed window is placed in parallel with high-quality insulation, it is possible for heat to bypass the insulation and travel quickly through the window frame. Thermal bridging is also common in steel framed buildings. When upgrading the quality of insulation, the following advice should be taken into consideration [33]:

- Always use continuous insulation. If multiple layers of continuous insulation are required, care should be taken to stagger the layers.
- In steel framed buildings, multiple layers of insulation are required. Foam or thermal blocks can be used to prevent thermal bridging at supports or purlins.
- Window frames should include a thermal break. Furthermore, a window's frame should never extend past interior insulation.
- Concrete slab foundations should be insulated around the perimeter and on top of the slab.

Beyond insulation, the effectiveness of a building's envelope is heavily impacted by infiltration of air from the surroundings or exfiltration of air from the controlled environment.

Pressure testing can be used to detect leaks once the building has been constructed. Small leaks can be individually sealed or a continuous air barrier membrane can be used to control major air leakage. An air barrier system should include all building levels, exterior walls, and roof. In cold climates, a vestibule should be included at each regularly used entrance to prevent massive infiltration and exfiltration [33].

3.2.3 Temperature Setpoints

Adjusting a building's temperature setpoints is another low-cost solution that relies on occupant behavior more than a technological fix. Inexpensive energy prices have led inhabitants of developed countries to expect climate control at home, work, and in public venues. In fact, ASHRAE identifies 26 °C as the upper bound for thermal comfort, but research has shown this value is not universal [32][59]. Humans will adjust to higher temperatures over time, and control over ventilation and humidity may further increase comfort levels. In the summer, a reduction in humidity will enhance comfort levels by allowing evaporative cooling. During the winter, humidity can be raised to reduce evaporative cooling, and prevent dry skin and respiratory passages [4]. Another simple solution is to dress appropriately for a slightly warmer or cooling environment. Layering clothing allows building occupants to adjust to meet their own comfort needs.

3.2.4 Model Implementation

One suggested energy reduction measure was selected from each category and implemented on a scale consistent with the ASHRAE Handbook [32], AEDGs [33], and the 2004 commercial reference models [15]. The primary objective was to adjust fundamental building systems (building envelope, lighting, comfort) rather than individual components (HVAC or water heating). Screenshots from EnergyPlus are shown for each building modification in Figures 3.7, 3.8, 3.9, and 3.10. The object's name is circled, and the relevant parameters are indicated with an arrow.

Each building zone in a commercial reference model has a lighting intensity value and lighting schedule. To simulate reductions in lighting intensity that could represent any of the techniques described above, this value was adjusted for each zone and the effect on building energy consumption and other building systems was observed. To be consistent, zones in all three models were reduced by a percentage for each simulation. The lighting schedule is a function of the building occupancy schedule and was not adjusted. Changes to the building envelope focused on the R-value of exterior wall and roof insulation, and the U-factor of all windows. The U-factor was adjusted through a range of values. R-value was adjusted by first decreasing the thermal conductivity of the insulation, and by doubling insulation thickness. Window U-factor and insulation R-value were not modified simultaneously. Similar to the lighting intensity and window U-factor, temperature setpoints were adjusted through a range of values. Values for each simulation are listed in the results section.

3.3 Results

Results are displayed in the following order: medium office (Figure 3.11 – 3.14), primary school (Figure 3.15 – 3.18), and supermarket (Figure 3.19 – 3.22). For each building the order is: lighting intensity, window U-factor, insulation R-value, and temperature setpoints. The following abbreviations were used to conserve figure space: C for cooling, EH for electric heating, L for lighting, NGH for natural gas heating, P for pumps and fans, R for refrigeration, V for ventilation.

The medium office saw the largest reduction in CO_2 emissions with alternative temperature setpoints at 15.7%. This was followed closely by a reduction in lighting intensity (14.0%), reducing the window U-factors (6.2%), and increasing the insulation's R-value (3.6%). Alternatively, the primary school saw the largest change in CO_2 emissions with a reduction in lighting intensity (22.7%). This was followed by temperature setpoints (10.4%), insulation (2.8%), and then windows (1.1%). The supermarket resembles the medium office building with temperature setpoints exhibiting the largest reduction (16.6%), and lighting intensity at (8.7%). However, like the primary school, insulation (2.6%) has a larger impact then window U-factor (0.5%). Table 3.4 summarizes these results, while their significance and limitations are discussed in the next section.

3.4 Discussion

The primary objective of these simulations was to determine the reduction in CO_2 emissions resulting from modifications to a building's construction or operational schedule in Salt Lake City. This simulation does not account for the building's surroundings and their effect on the total energy consumption. For example, a building that is shaded heavily by trees will not experience as large of a solar heat gain as one that is not shaded. This could decrease the building's cooling load, but it could also increase the total heating load. The net energy consumption depends on the location's climate, building construction, occupancy, and operation together. This research gives powerful insight into the benefits of building energy modeling

For all three buildings, reductions in lighting intensity and changes to temperature setpoints were proven to reduce CO_2 emissions more than decreased window U-factors or increased insulation R-values. Variation in the benefits of each can be attributed to the building design. As expected, changing a building's temperature setpoints directly affects the energy required for heating or cooling. Furthermore, a slight variation in ventilation energy accompanies the change in temperature. Tighter temperature setpoints will increase ventilation energy since the system operates more frequently. All three building models have identical default temperature setpoints, as well as insulation R-values and window U-factors (Table 3.3). The medium office has a slightly higher heating efficiency, while the primary school and supermarket have a larger cooling COP. A closer examination of the baseline energy consumption yields values for heating and cooling intensity. A large heating or cooling intensity indicates a large potential for reduction. Initial observation of these data in Figures 3.14, 3.18, and 3.22 can be misleading as it may appear that the office achieves a larger reduction in CO_2 than the primary school. It is important to look at both the percent reduction in CO_2 emissions, and the absolute reduction in energy consumption. Energy consumption and CO_2 emissions are linearly related. For all three buildings, altering the temperature setpoints is affected by diminishing returns. A tighter temperature band requires more energy to maintain. As this range is relaxed, the building gradually approaches zero energy required for heating and cooling. Unaffected energy categories include: lighting, equipment, pumps, and water systems. Assuming no changes are made to the building's HVAC system, the costs associated with this change are minimal; however, building occupants may reject changes to the temperature.

As for reductions in lighting intensity, it is obvious that the main energy category affected is lighting. Notice that this is accompanied by a slight reduction in cooling and a slight increase in heating. Similar to the temperature setpoint simulations, a large baseline value of lighting intensity indicates a large potential for reduction. Unaffected energy categories include: equipment, pumps, and water systems. Determining the exact costs associated with a reduction in lighting intensity is highly dependent on how the change is implemented. If lighting intensity is reduced through daylighting, it might increase design and construction costs, but will not affect the operating cost. Upgrading to more efficient lighting fixtures and ballast will increase the initial construction cost, but will reduce operating costs. It is difficult to assess economic benefit without a specific design and local cost estimates. Again, occupant comfort should be considered during the design process.

Depending on the building design, decreasing window U-factor and increasing insulation R-value will exhibit varying degrees of success. For example, the supermarket benefited very little to reductions in window U-factor. Notice that the supermarket has a very small

WWR. Conversely, this change was more beneficial in the medium office because of a high WWR. However, notice the primary school also has a high value for WWR, but does not experience the same improvement. This could be related to the primary school's SAV. The emissions reduction resulting from increased insulation R-value was not as beneficial as expected and could be the result of thermal bridging through window surfaces. These two changes primarily affected heating, cooling, and ventilation loads. A detailed economic analysis is not possible without a specific design and local cost estimates.

3.5 Conclusions and Future Work

The aim of this chapter was to demonstrate how building energy modeling software can be used to estimate reductions in energy consumption and CO_2 emissions resulting from changes to the building's design, operation, or occupancy. For the three commercial reference models simulated in Salt Lake City, the largest reduction in CO_2 emissions were achieved through changes in temperature setpoints and lighting reductions. Decreased window U-factors and increased insulation R-values were less successful. The major limitation of this chapter is the lack of specific economic data. Without economic data, it is not possible to prioritize the order in which efficiency upgrades should be implemented. There is even a chance that it would be more beneficial to incorporate site-specific energy generation first.

There are several directions that could be taken for future research. One possibility would be to expand the energy efficiency upgrades incorporated with the commercial reference models. For example, this could include modeling and upgrading specific mechanical components such as chillers, heat rejection, air handling units, etc. Furthermore, the results presented in this chapter could be expanded to gain a deeper understanding of why some changes are more successful than others. For example, how does the relationship between SAV, WWR, window U-factor, and insulation R-value affect energy reductions from decreased window U-factors and insulation R-values? Another option would be to create models for specific buildings on the University of Utah's campus. Building should be chosen according to the availability of energy demand and occupancy data so that the model can be validated. With specific building models it would be possible to obtain detailed economic data for energy efficiency upgrades. Beyond creating specific building models, it would also be useful to create a profile of Salt Lake City's individual building stock. Commercial reference models could be built around these data and used to model city-wide energy emissions.

Table 3.1. HDD and CDD for a selection of cities in the U.S. (Base = 18.3°C) [32]

City, State	**HDD [°C]**	**CDD [°C]**
Phoenix, AZ	513	2570
Denver, CO	3311	432
Miami, FL	70	2521
Duluth, MN	5171	117
Charleston, SC	1044	1309
Salt Lake City, UT	3059	677

Table 3.2. CO_2 emission conversion factors for electricity and natural gas

	Electricity [60]	**Natural Gas** [61]	**Units**
Conversion Factor	0.6000	0.1810	[kgCO_2/kWh]

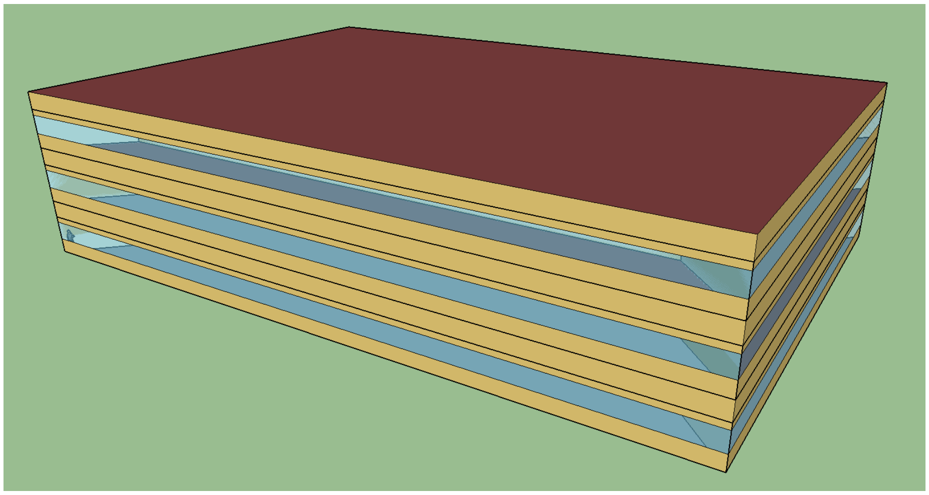

Figure 3.1. Medium office commercial model displayed in SketchUp 2014 with the OpenStudio plug-in

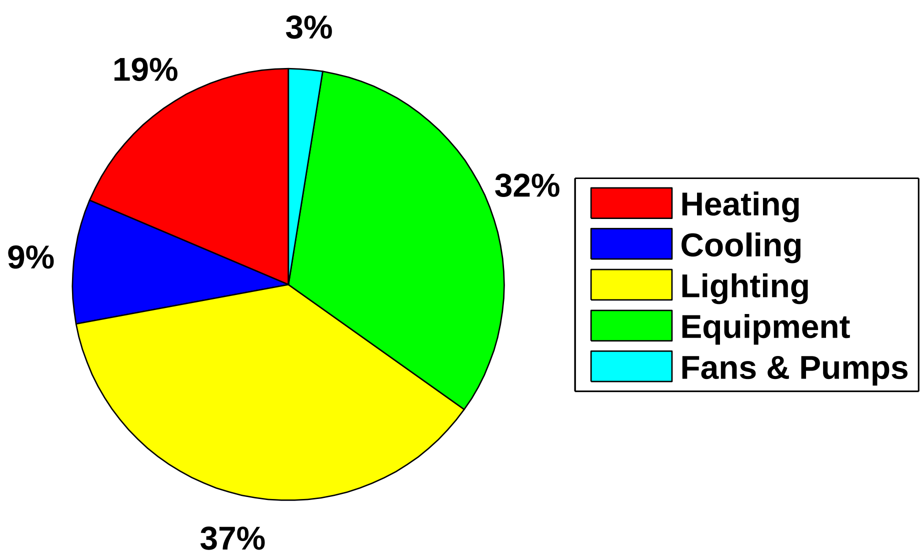

Figure 3.2. Baseline energy consumption breakdown for the medium office

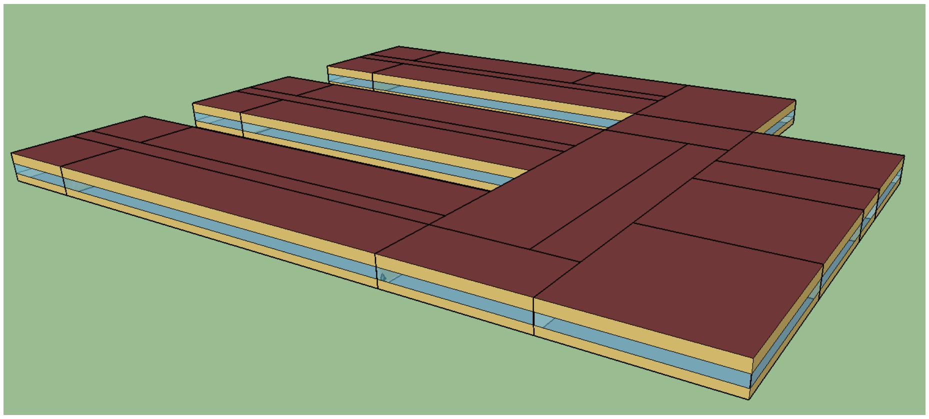

Figure 3.3. Primary school commercial model displayed in SketchUp 2014 with the OpenStudio plug-in

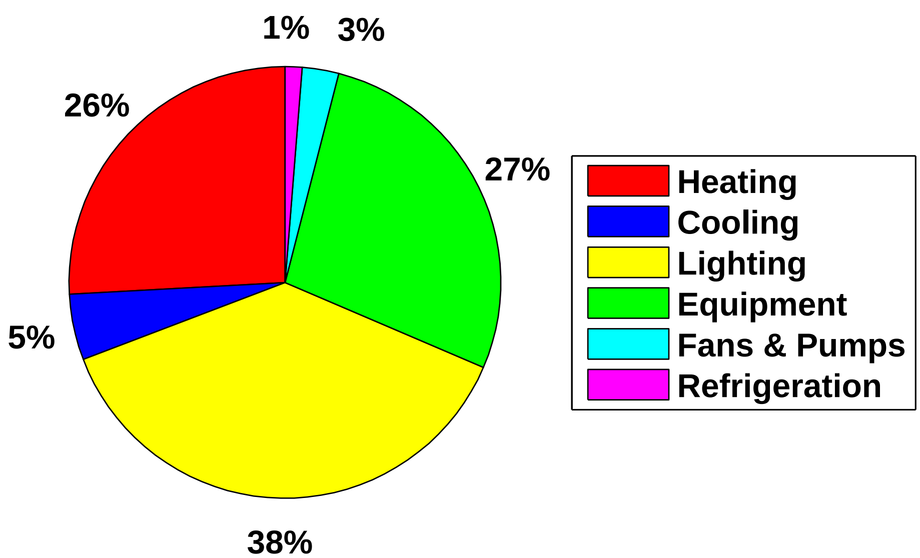

Figure 3.4. Baseline energy consumption breakdown for the primary school

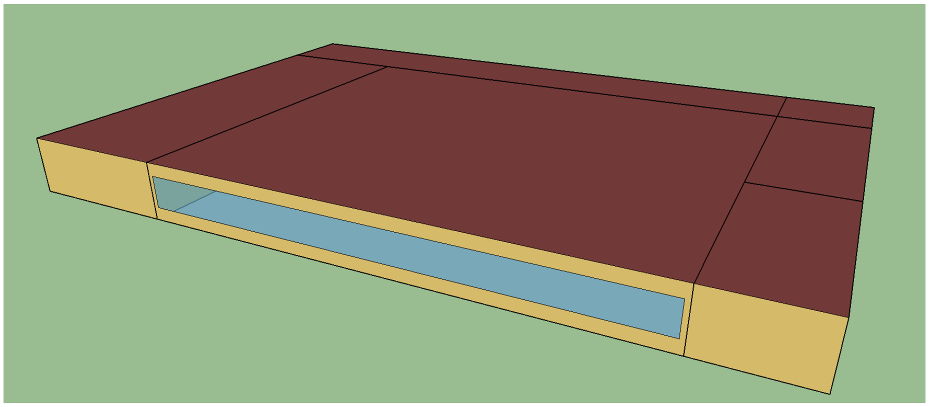

Figure 3.5. Supermarket commercial model displayed in SketchUp 2014 with the OpenStudio plug-in

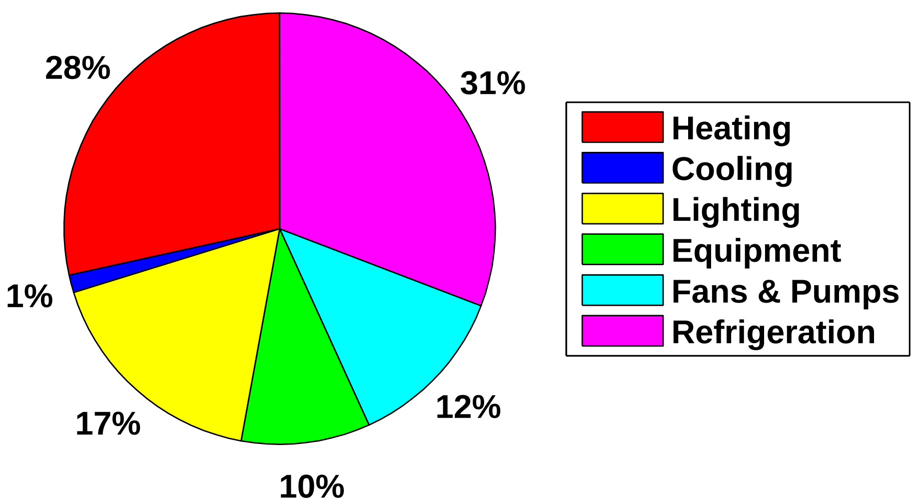

Figure 3.6. Baseline energy consumption breakdown for the supermarket

Table 3.3. Commercial model baseline performance data

Building Metric	Units	Medium Office	Primary School	Supermarket
Model Envelope				
Number of floors	-	3	1	1
Floor area	[m^2]	4,982	6,871	4,180
Roof area	[m^2]	1,660	6,871	4,180
Building volume	[m^3]	19,893	27,484	25,501
Surface area	[m^2]	3,654	9,383	5,791
Wall area	[m^2]	1,993	2,512	1,610
Insulation R-Value	[K/W]	1.83	1.83	1.83
Roof R-Value	[K/W]	3.26	3.26	3.26
Window area	[m^3]	654	886	175
U-Factor	[W/m^2K]	3.35	3.35	3.35
SHGC	-	0.39	0.39	0.39
SAV	-	0.18	0.34	0.23
WWR	-	0.33	0.35	0.11
Foundation type	-	Concrete	Concrete	Concrete
Frame material	-	Steel	Steel	Concrete
Occupancy				
Maximum	-	268	1,539	326
HVAC Parameters				
Electric Heating Eff.	–	1	–	–
Gas Heating Eff.	–	0.80	0.78–0.80	0.78–0.80
Cooling COP	–	2.80	3.23–3.60	3.13–3.60
Heating Intensity	[GJ/m^2]	0.12	0.20	0.69
Cooling Intensity	[GJ/m^2]	0.06	0.04	0.03
Occupied Setpoint				
Cooling	[°C]	24.0	24.0	24.0
Heating	[°C]	21.0	21.0	21.0
Unoccupied Setpoint				
Cooling	[°C]	26.7	27.0	30.0
Heating	[°C]	15.6	16.0	15.6
Electric Load				
Lighting Intensity	[W/m^2]	16.89	19.55	27.07
Equipment Intensity	[W/m^2]	10.76	16.40	10.99
Baseline Energy				
Heating	[GJ]	615.16	1,381.26	2,902.27
Cooling	[GJ]	307.51	264.15	135.10
Lighting	[GJ]	1,231.47	2,016.17	1,770.52
Equipment	[GJ]	1,066.52	1,464.57	984.82
Fans & Pumps	[GJ]	84.46	146.31	1262.45
Refrigeration	[GJ]	0.00	68.35	3142.57

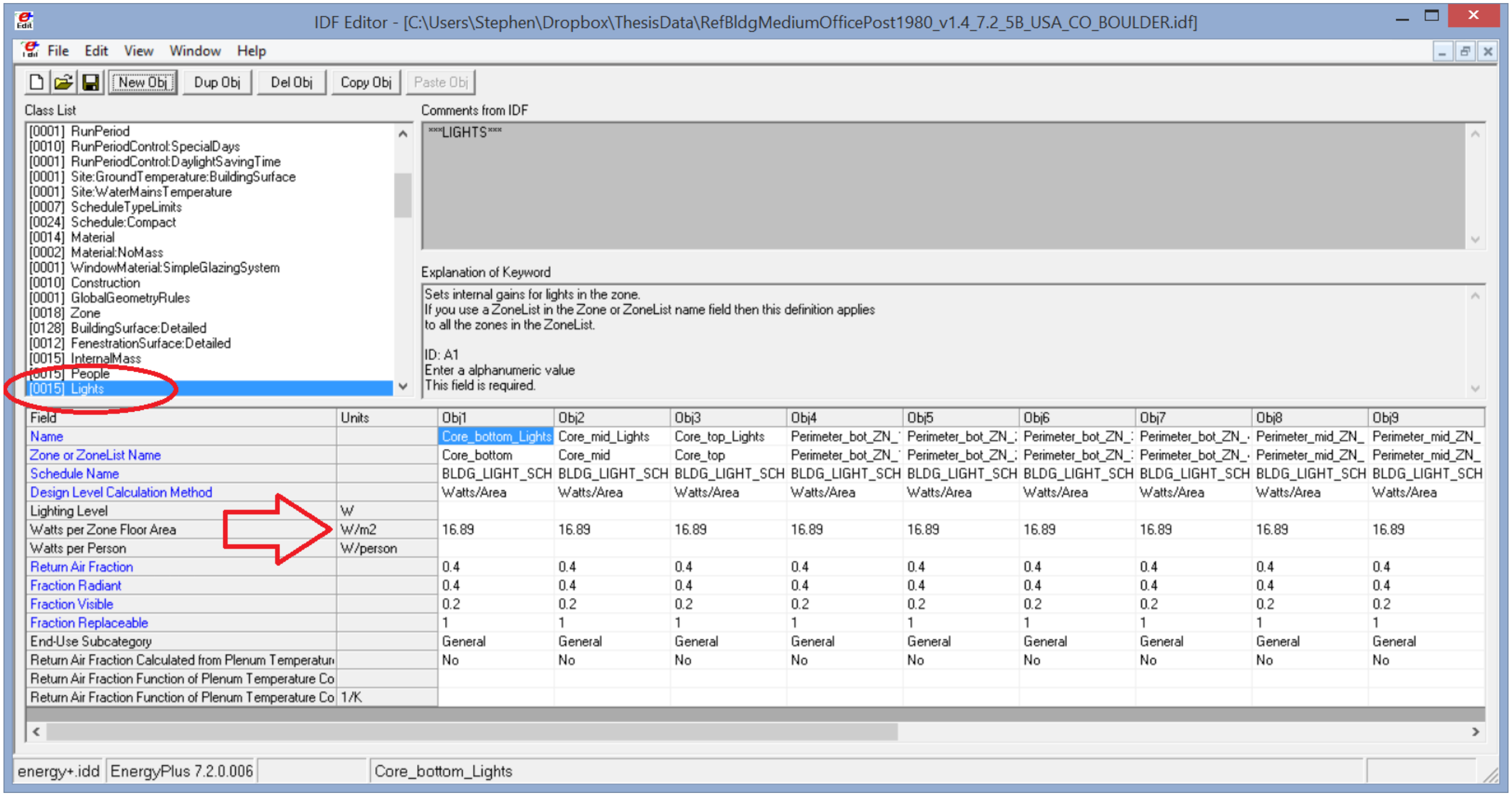

Figure 3.7. Lighting intensity is adjusted within the model's "Lights" object.

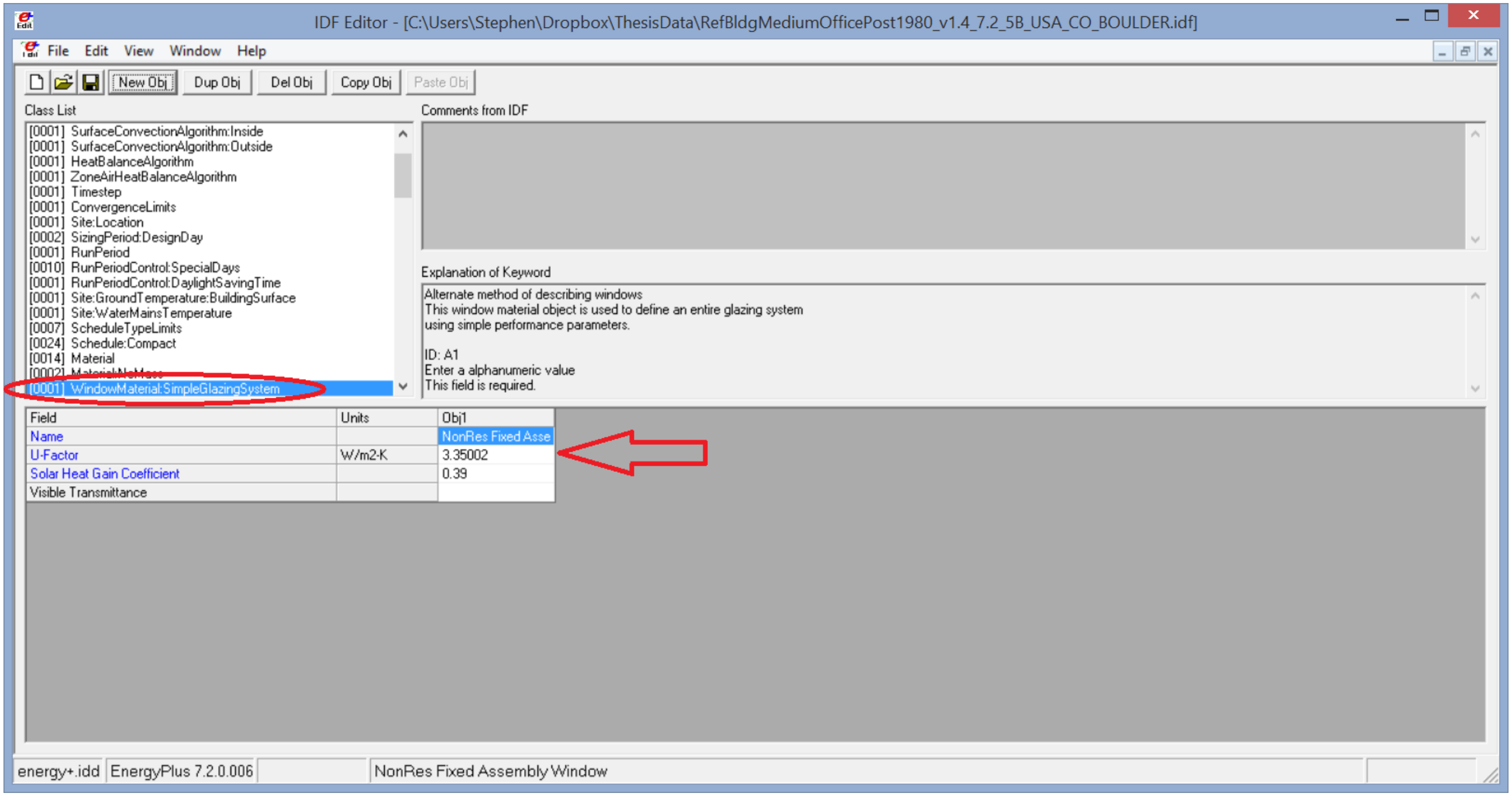

Figure 3.8. Window U-factor is adjusted within the model's "WindowMaterial:SimpleGlazingSystem" object.

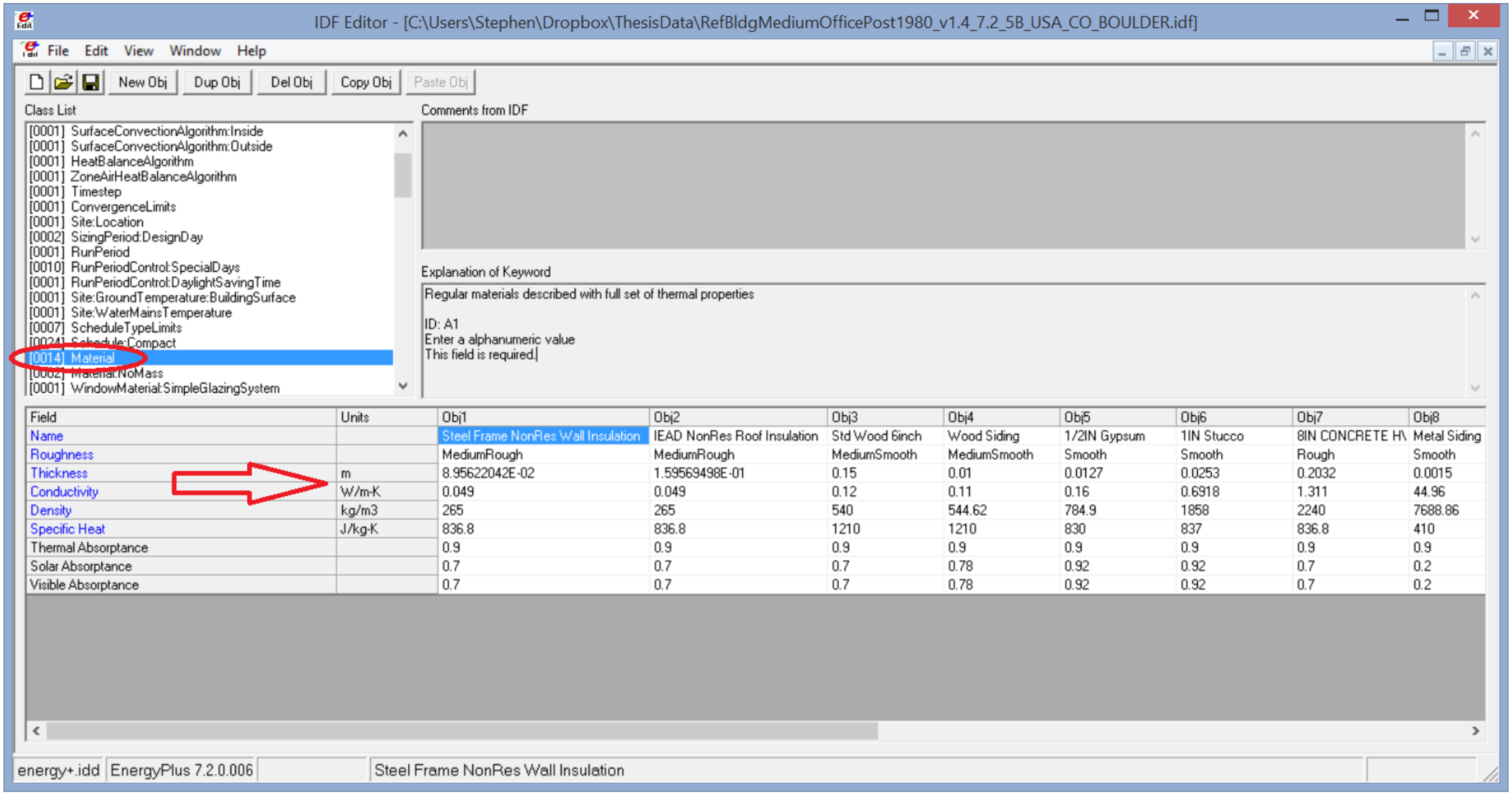

Figure 3.9. Insulation R-values are adjusted using the "Material" object. Both the insulation thickness and conductivity affect the R-value.

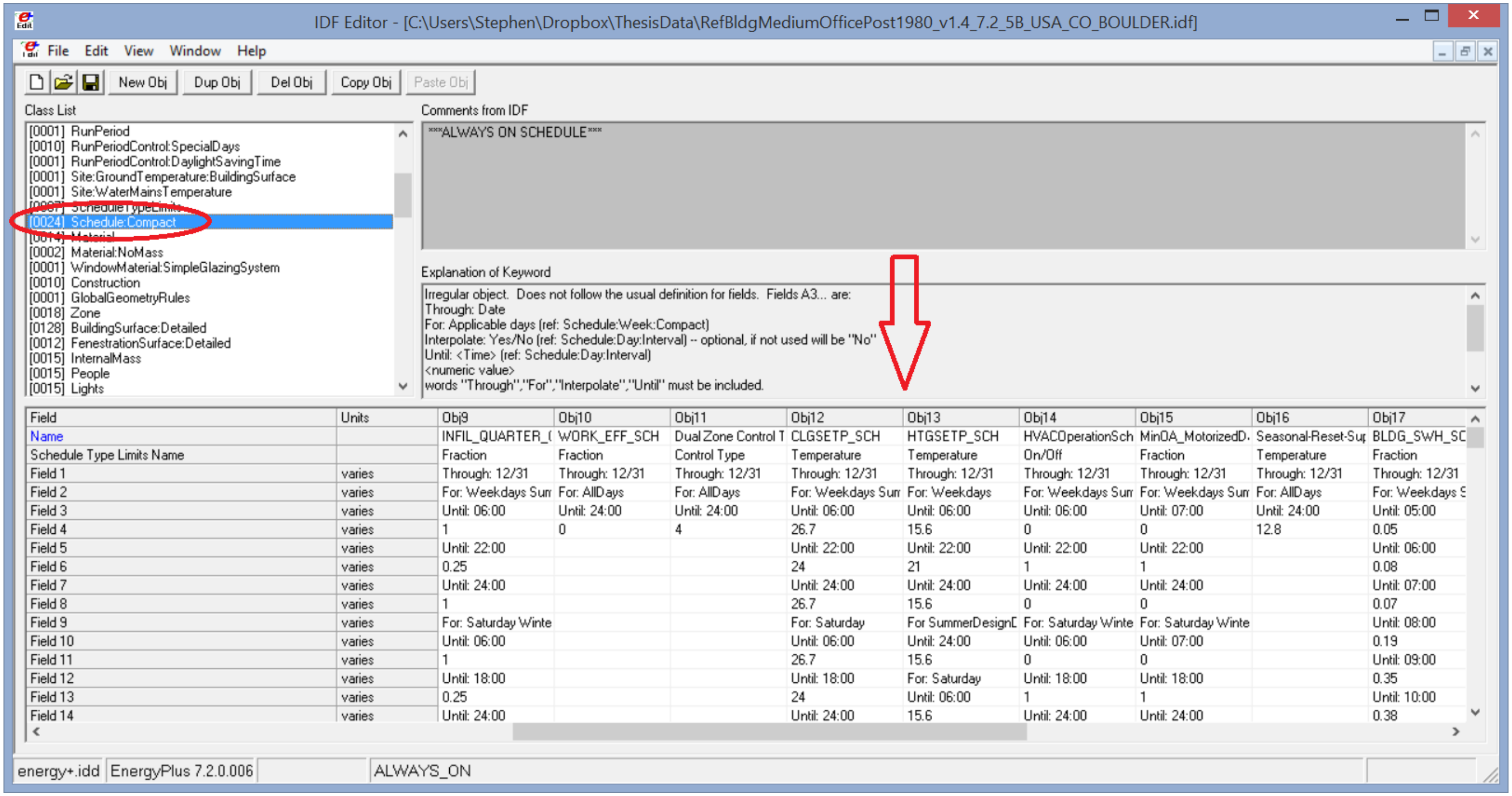

Figure 3.10. Temperature setpoints are adjusted within the "Schedule:Compact" object. CLGSETP_SCH and HTGSETP_SCH control the cooling and heating setpoints, respectively.

Table 3.4. Results summary for CO_2 emissions reductions

	Medium Office	**Primary School**	**Supermarket**
Lighting Intensity [%]	14.0	22.7	8.7
Temperature Setpoint [%]	15.7	10.4	16.6
Insulation R-value [%]	3.6	2.8	2.6
Window U-factor [%]	6.2	1.1	0.5

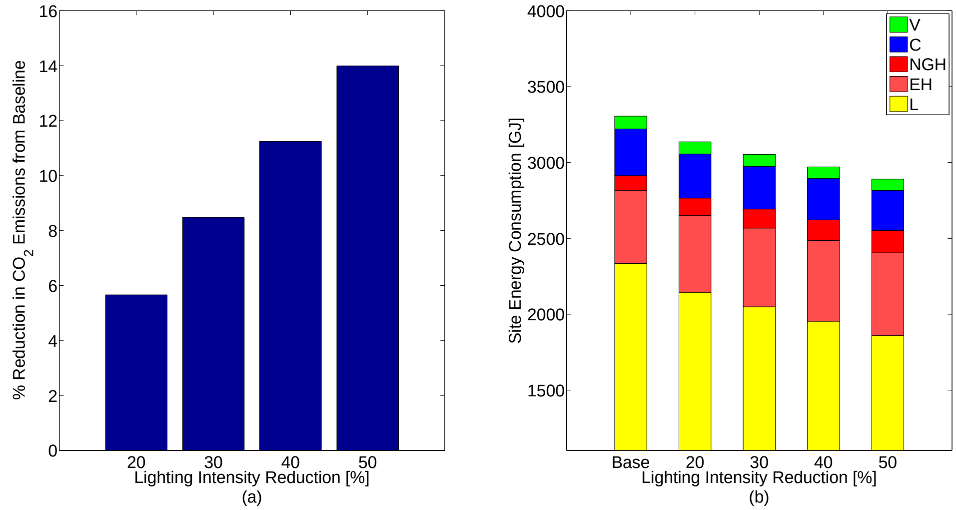

Figure 3.11. Effect of lighting intensity on (a) CO_2 emissions and (b) energy consumption for the medium office

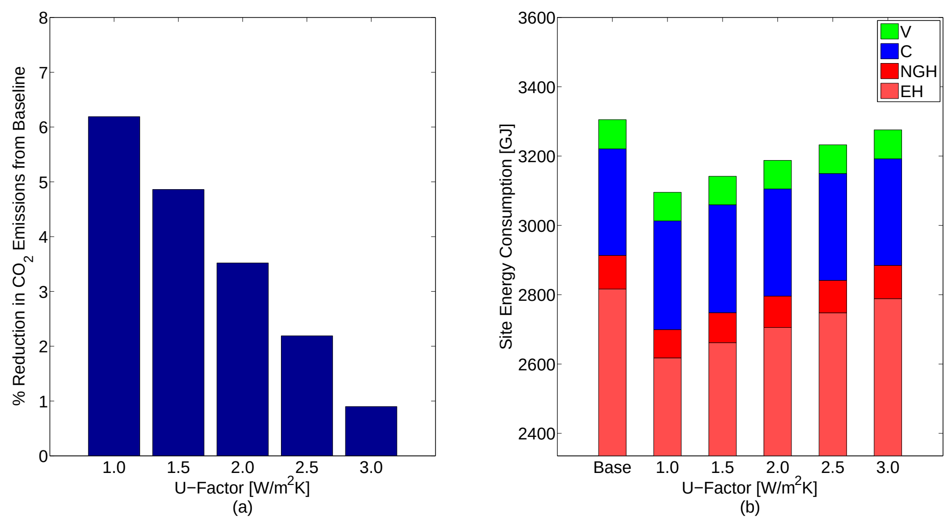

Figure 3.12. Effect of window U-factor on (a) CO_2 emissions and (b) energy consumption for the medium office

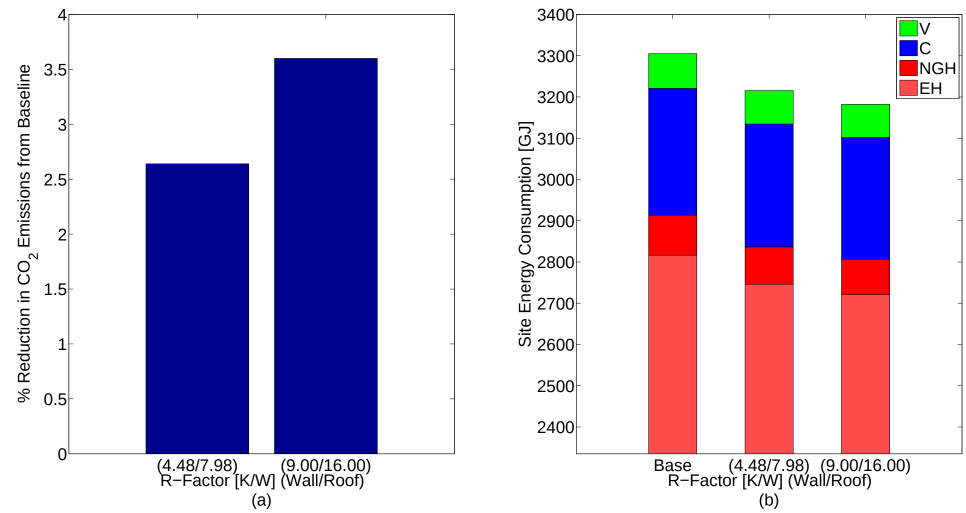

Figure 3.13. Effect of wall insulation R-value on (a) CO_2 emissions and (b) energy consumption for the medium office

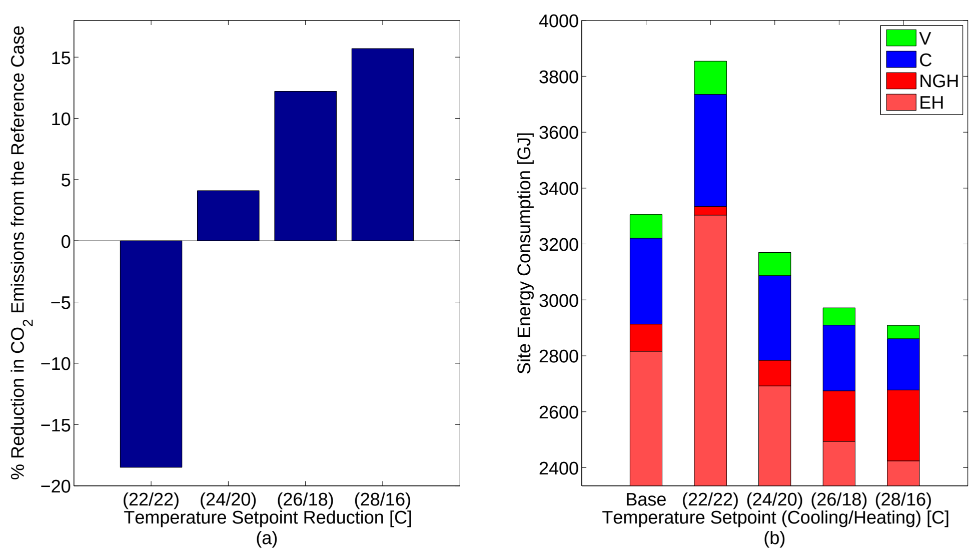

Figure 3.14. Effect of temperature setpoints on (a) CO_2 emissions and (b) energy consumption for the medium office

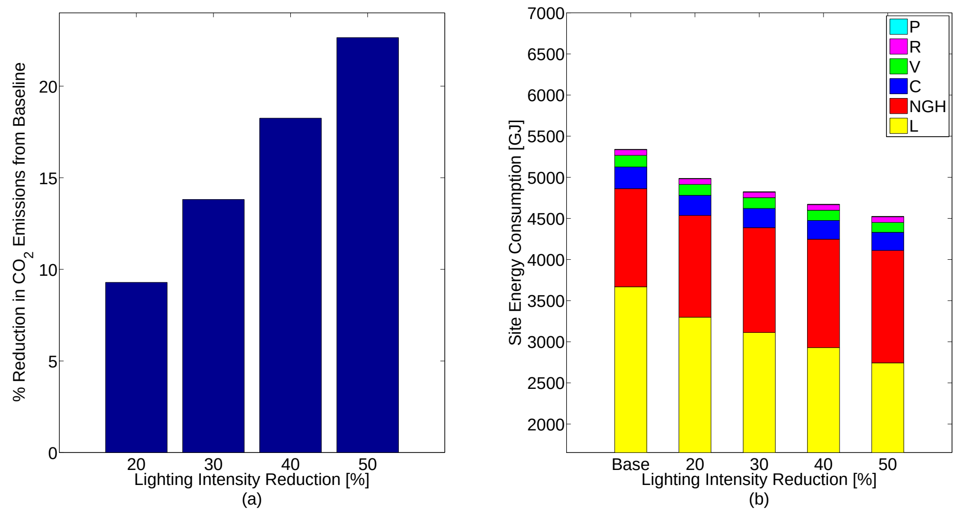

Figure 3.15. Effect of lighting intensity on (a) CO_2 emissions and (b) energy consumption for the primary school

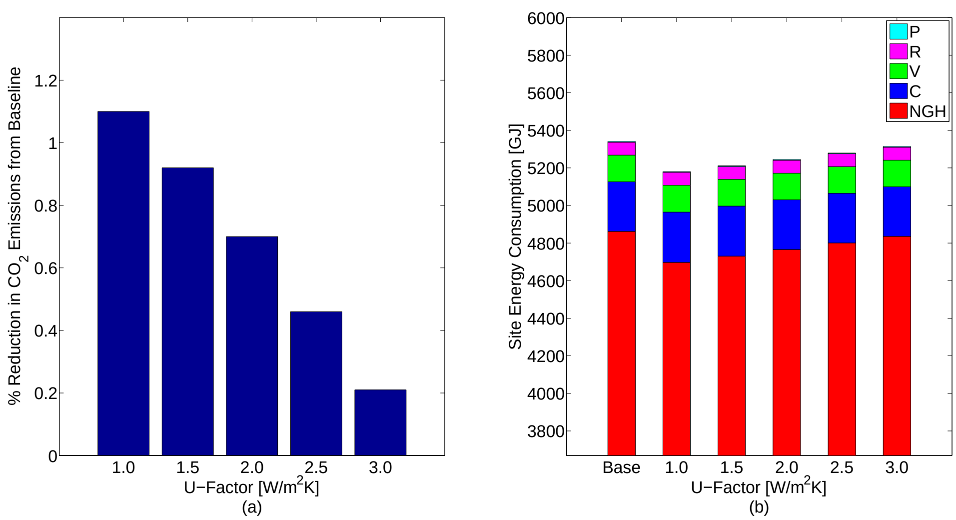

Figure 3.16. Effect of window U-factor on (a) CO_2 emissions and (b) energy consumption for the primary school

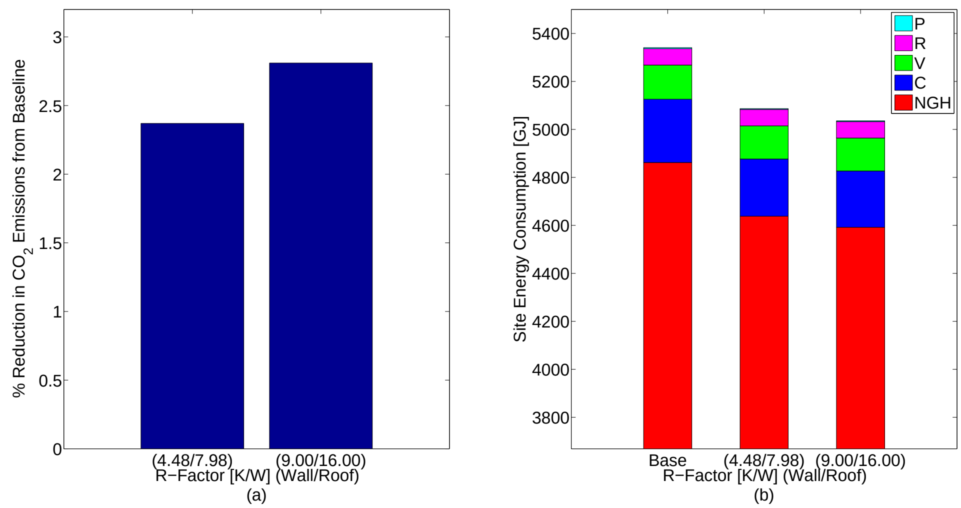

Figure 3.17. Effect of wall insulation R-value on (a) CO_2 emissions and (b) energy consumption for the primary school

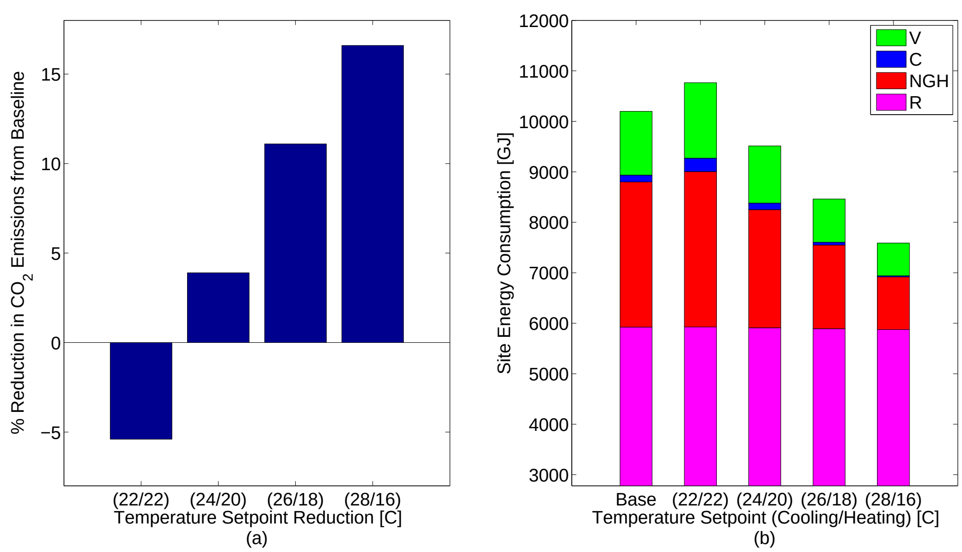

Figure 3.18. Effect of temperature setpoints on (a) CO_2 emissions and (b) energy consumption for the primary school

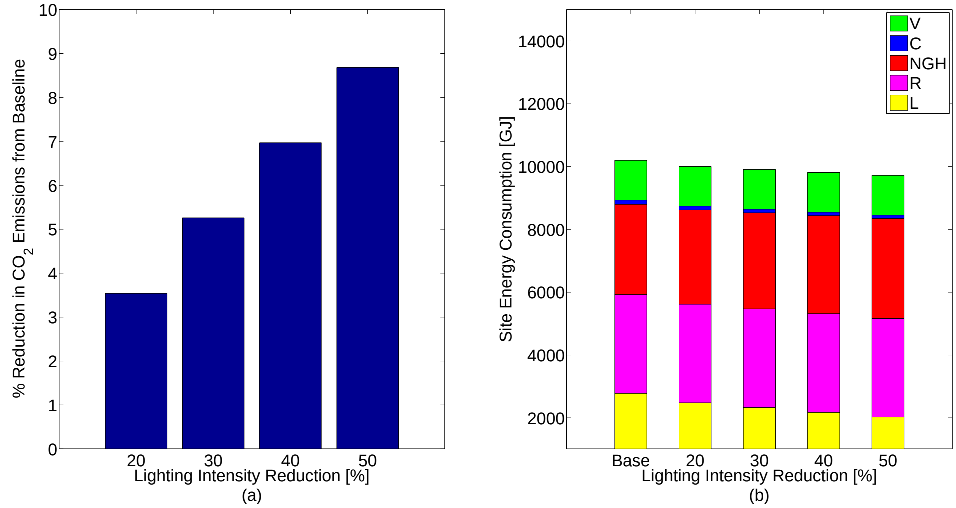

Figure 3.19. Effect of lighting intensity on (a) CO_2 emissions and (b) energy consumption for the supermarket

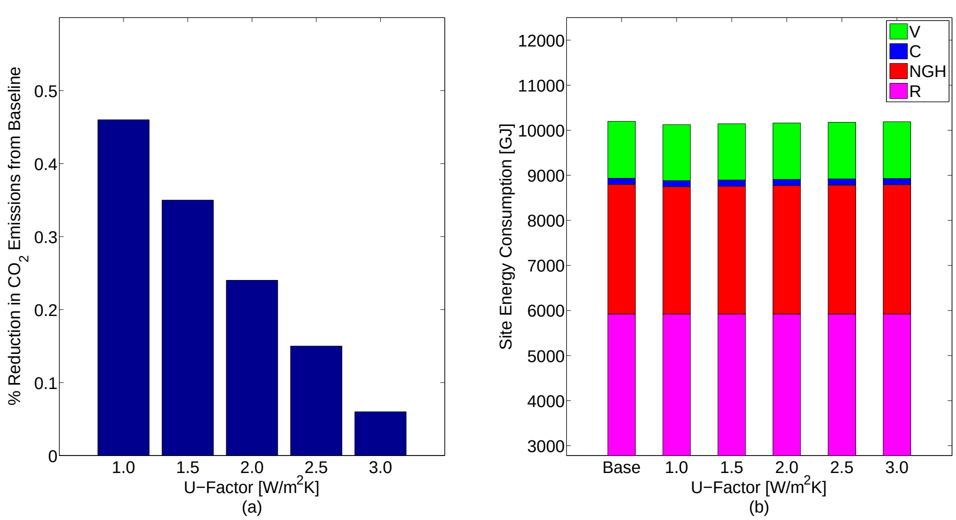

Figure 3.20. Effect of window U-factor on (a) CO_2 emissions and (b) energy consumption for the supermarket

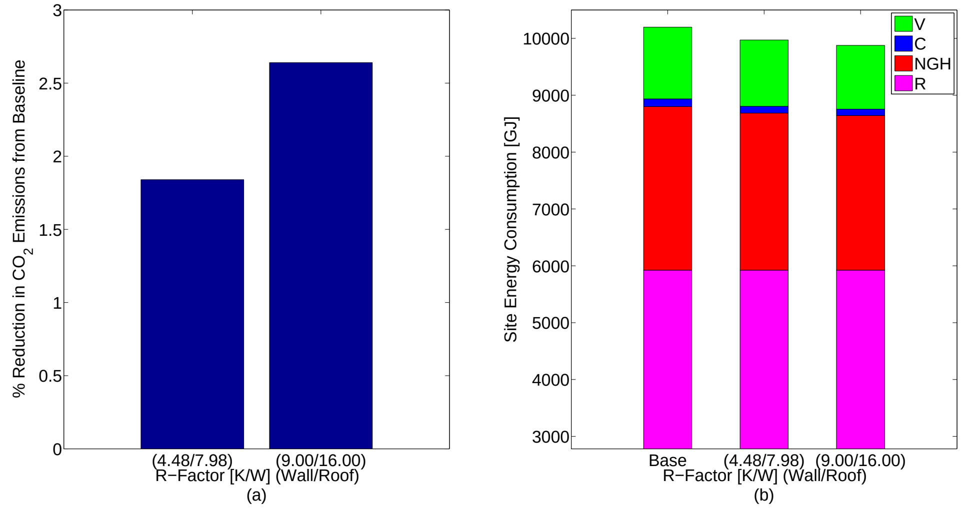

Figure 3.21. Effect of wall insulation R-value on (a) CO_2 emissions and (b) energy consumption for the supermarket

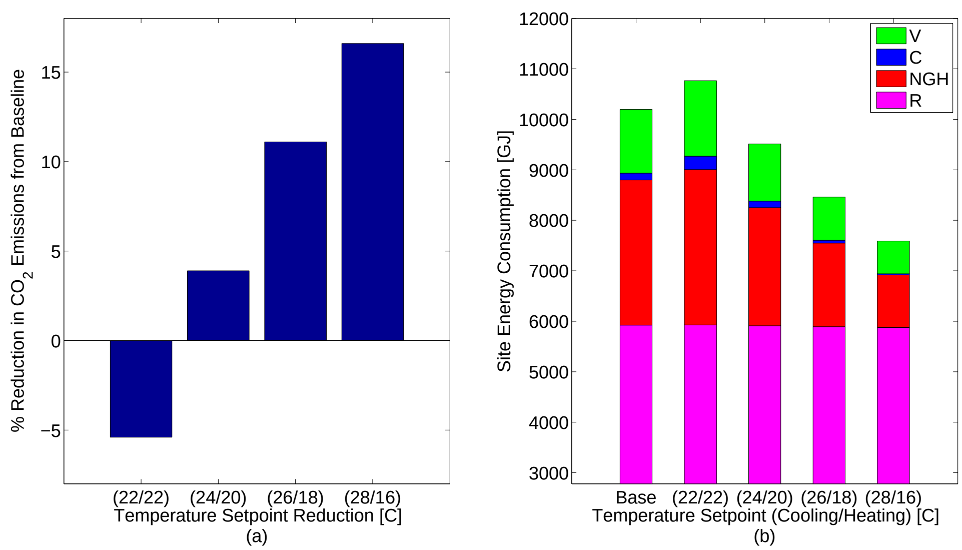

Figure 3.22. Effect of temperature setpoints on (a) CO_2 emissions and (b) energy consumption for the supermarket

CHAPTER 4

OPTIMAL PHOTOVOLTAIC SIZING

Beyond energy efficiency and conservation policy, the addition of site-specific sustainable energy generation presents another opportunity to reduce a building's CO_2 emissions. Rooftop PV is a good fit for Salt Lake City because of high average annual irradiation levels [4, 38, 39]. Economic benefit, environmental benefit, and the available area will influence the size of the PV array.

In this chapter, an expanded demand matching method based on the work of Borowy is presented [62]. Demand matching uses the method of least squares to maximize the benefits of PV, without oversizing the system. An oversized system may only be desirable when the rate for suplus electricity from the utility is high. Demand matching focuses purely on the difference between production and the building's demand; however, additional terms may be added to mitigate the environmental or economic impact. Additionally, it is possible to expand the demand matching technique to determine the optimal array tilt angle. Results from this analysis are specified in terms of total cost and CO_2 emissions. MATLAB code for these techniques is included in Appendix B (GoldenSearch.m and SaMatch.m) [63].

4.1 Demand Matching Optimization

This sizing technique minimizes the excess or deficit of a PV array with regards to a specific building's demand. In other words, demand matching attempts to prevent oversizing or undersizing of the PV array. Demand matching assumes the system designer has access to building demand and solar radiation data, or can accurately predict these values, for at least a year. If less data are available, there is a chance the array will not be optimally sized. For example, if data are only available for the month of July, then it is likely the system will be undersized in winter months. This is the result of higher solar availability during July. When solar irradiation levels are large, a smaller PV array area is required to produce a given amount of electricity. This example assumes that July receives a larger amount of solar radiation than all other months. The concept of demand matching is written mathematically in Equation 4.1. E_d represents the building's electricity demand, E_{PV} is the electricity supplied by the PV system, and n is the total number of time steps.

$$\min \sum_{i=1}^{n} (E_{d(i)} - E_{PV(i)})^2 \tag{4.1}$$

The square in Equation 4.1 is necessary to treat an undersized system equally with an oversized system. Equation 4.1 may be rewritten as:

$$\min \sum_{i=1}^{n} (E_{d(i)} - A_S \eta_{PV} \eta_{IN} I_{GI(i)})^2 \tag{4.2}$$

In Equation 4.2, the only unknown variable is A_S, or the surface area of the PV array. η_{PV}, η_{IN}, and $I_{GI(i)}$ represent the PV efficiency, inverter efficiency, and solar irradiation rate, respectively. Equation 4.2 was solved explicitly in matrix form (Equation 4.3).

$$As = [(\eta_{PV}\eta_{IN}\boldsymbol{I_{GI}})^T(\eta_{PV}\eta_{IN}\boldsymbol{I_{GI}})]^{-1}(\eta_{PV}\eta_{IN}\boldsymbol{I_{GI}})\boldsymbol{E_d} \tag{4.3}$$

In Equation 4.3, $\boldsymbol{E_d}$ and $\boldsymbol{I_{GI}}$ are vectors with length corresponding to the number of time steps. An examination of the function (Equation 4.2) determines that A_S must be larger than zero. Any value less than zero will increase the function value. Furthermore, it is not physically possible to have a negative PV array area. If the solution is larger than the area available to the building owner or designer, this indicates it is not possible to optimally size a PV system with the technology currently available. If there is a limit of the available area for the array, the system designer should fill that space.

In order to account for economic or environmental impact, the above equations may be modified using penalty terms and conditional statements in MATLAB. The penalty term effectively shifts the recommended area based on the designer's values. For example, when the building's electricity demand is less than the electricity produced by the PV system, the following penalty term is applied to the PV electricity production.

$$x = \begin{cases} \frac{C_G}{C_S}, & \text{if } E_{PV} > E_d \\ 1, & \text{otherwise} \end{cases} \tag{4.4}$$

C_G represents the cost of grid electricity while C_S is the rate the utility returns for surplus electricity. The penalty term is applied to the second term of Equation 4.2 when E_{PV} is greater than E_d as shown in Equation 4.5.

$$\min_{A_S} \sum_{i=1}^{n} (E_{d(i)} - xA_S \eta_{PV} \eta_{IN} I_{GI(i)})^2 \tag{4.5}$$

When the price of grid electricity greatly outweighs the export value of surplus electricity, the penalty term reduces the size of the recommended PV array by increasing the weight of the system's output. The recommended area decreases in order to compensate.

Similarly, when the building's electricity demand is greater than the electricity produced by the PV system, the following penalty term (Equation 4.6) may be used to increase the recommended system size. It is only applied at time steps where E_d is greater than E_{PV}. This penalty term is useful when CO_2 emissions are a concern.

$$y = \begin{cases} \frac{EF_{min}}{EF_G}, & \text{if } E_d > E_{PV} \\ 1, & \text{otherwise} \end{cases} \tag{4.6}$$

EF_{min} represents the smallest regional electricity emissions factor found in the United States, and EF_G represents the local emissions factor. When the local emissions factor is much larger than the national minimum, the penalty term increases the size of the recommended PV system by decreasing the weight of the system's output (Equation 4.7).

$$\min \sum_{i=1}^{n} (E_{d(i)} - y A_S \eta_{PV} \eta_{IN} I_{GI(i)})^2 \tag{4.7}$$

4.2 PV Array Tilt Angle Optimization

The term for solar radiation in Equation 4.2 may be expanded to account for an angled array (Equation 4.8). When substituted back into Equation 4.2, the optimal system depends on two independent variables: array angle and array area (Equation 4.9). Solar altitude angle data are included in the TMY3 weather file along with solar radiation data. Figure 4.1 illustrates the concept of incident radiation on an angled surface.

$$I_{GI(i)} = I_{GT(i)} sin(\alpha + \beta) \tag{4.8}$$

$$\min \sum_{i=1}^{n} (E_{d(i)} - A_S \eta_{PV} \eta_{IN} I_{GT(i)} sin(\alpha + \beta))^2 \tag{4.9}$$

With the inclusion of the PV array angle, this problem becomes nonlinear and can no longer be solved using Equation 4.3. The golden section search algorithm was used to determine at which angle the demand matching approach recommended the least area. With the golden section search, the designer determines the range of tilt angles over which the PV array may be installed. The algorithm substitutes angle values within this range into Equation 4.9, and reduces the equation to the form of Equation 4.3. The algorithm determines which angle requires the least array area for the supplied range of angles. Figure 4.2 demonstrates the dependence of array area on tilt angle.

4.3 Sizing Parameters

Important parameters required for analysis in Salt Lake City, UT are listed in Table 4.1. Values for both the array efficiency and the inverter efficiency were chosen to be reasonable values for the current state of the respective technology. The electricity cost shown was reported on the Utah Geological Survey website [64], and is useful for quick calculations. However, a detailed analysis in Salt Lake City should use the price summary sheet provided by Rocky Mountain Power [49] for improved accuracy. This case study relies on values that went into effect on November 1, 2014. Unlike the flat rate per energy consumption provided by the Utah Geological Society, the rates set by Rocky Mountain Power include a power charge, as well as the standard energy charge. The power charge is calculated based on the maximum power consumption averaged over 15-minute intervals for the entire month. Power and energy charges are set for the following two time frames: May through September and October through April. The surplus rate shown is the value included on the default commercial billing schedule.

In this case, the LCOE was calculated over a 30-year period with an after tax interest rate of 6.5%. Furthermore, this value assumes that the energy generation resource will become active in the year 2018. An earlier construction date would increase the LCOE value. Additionally, several emissions factors are listed in Table 4.1. The first is the emissions factor for power generation in Utah. Notice this is the same value listed in Table 3.2 and used in the analysis of Chapter 3. The minimum emission factor represents the national minimum, which corresponds to a region in Alaska [60]. This value is intended for use with Equation 4.6. Finally, the PV emissions factor represents the CO_2 emission created indirectly through the generation of electricity using PV panels. While the operation of a PV panel does not produce any emissions, CO_2 is created during manufacturing, transportation, construction, demolition, and disposal. The value shown is representative of these emissions spread over the panel's useful lifetime.

4.4 Results

In order to demonstrate the application of the demand matching equation, Figure 4.3 was generated using a summation of weekly data. Weekly totals create a more organized plot; however, it is not possible to see surplus generation at this resolution. At the hourly level, it is possible to see surplus generation, but the plot becomes difficult to read with a full year worth of data. Figure 4.4 shows (a) hourly data for a week starting on January 21st (Saturday) and (b) a week starting on July 21st (Friday). Both plots were created with the data generated for the improved medium office building. Notice that both the building demand and electricity generated with PV are larger in July. The two instances of surplus electricity in July happen on the weekend. In January, there is surplus generation on the weekend, and on Tuesday.

Table 4.2 summarizes the results of the demand matching simulation. The baseline electrical demand is included for reference. Shown from left to right is the optimal array angle, the optimal array area, the annual electricity demand after the PV installation, and the annual surplus electricity. The difference between the baseline demand and the building demand is equal to the amount of electricity generated by the PV array.

Beyond the reduction in demand, the total operating cost and reduction in CO_2 emissions are two important motivating factors for the building owner or designer. Figures 4.5,4.6, and 4.7 demonstrate the trade off between cost and CO_2 emissions for the medium office, primary school, and supermarket, respectively.

4.5 Discussion

From Figure 4.3, it is clear that one of the strengths of the demand matching method is that the system supply is closest to the building's demand during summer months. This is the result of higher solar radiation during the summer. Beyond the abundance of solar radiation at this location, this result indicates that PV is a good match for Salt Lake City because Rocky Mountain Power increases both commercial power and energy rates between May and September.

From Figure 4.2, the tilt angle is determined to be significant. Typically, designers set the tilt angle to the latitude of the site. For Salt Lake City, this is approximately 40 degrees. The recommended array size and angles are listed in Table 4.2. In this case, the difference between the recommended angle and the site latitude is small and does not translate into a large reduction in area. However, if the designer is considering mounting PV array's directly on a roof, the costs associated with the reduced area and an angled roof mount should be compared. The recommended array size and angle listed in Table 4.2 are influenced by the building's total demand, as well as the demand pattern. In other words, is the building's demand evenly distributed, or is it concentrated over a few peak hours? Furthermore, when the PV array is optimized for a building with the efficiency modifications described in Chapter 3, the building's demand pattern will influence variations in the array angle, the percent reduction in electricity demand from the grid, and surplus electricity available for export to the utility.

From Table 4.3, it is clear that solar PV alone is not feasible for the selected models from a purely economic standpoint. While the annual operating cost for the energy efficient buildings is in fact lower than the default operating cost, this does not include the construction costs associated with the efficiency measures described in Chapter 3. If the costs associated with energy efficiency upgrades exceeds the savings from a reduced PV size, then PV should be installed first. This observation is based solely on economics. However, if achievable reductions in CO_2 emissions are also a motivating factor, it should be noted that it is possible to reduce these emissions by 62%, 58%, and 57% for the medium office, primary school, and supermarket, respectively. CO_2 emissions could play a larger role in the decision-making process with policy to restrict or economically penalize a building's emissions.

Figures 4.5, 4.6, and 4.7 visually demonstrate the trade-off between cost and emissions. All three figures have approximately the same shape, but axis values vary considerably. Due to the economics of the LCOE and pricing structure, price increases almost linearly for all three buildings. Notice that the slope of the cost curve is less steep with a small array size. This slight increase in price corresponds to a large decrease in CO_2 emissions and a case could be made for small PV arrays. Otherwise, all three buildings achieve their minimum operating cost without a PV array. Alternatively, CO_2 emissions decrease sharply before beginning to increase gradually. This is the result of the emission factor associated with solar PV technology. Since this value is not zero, it is not possible to reach net-zero source emissions. Minimum emissions are achieved with an array size of approximately 1500, 2000, and 4000 square meters for the medium office, primary school, and supermarket, respectively. In order to minimize both cost and emissions together, the designer should choose the point of intersection of the two variables. The social cost of carbon, or another policy measure, must be used to convert CO_2 emissions to a comparable dollar value. From the analysis presented in this chapter, it is possible to determine whether to perform energy efficiency upgrades before or after the installation of PV. If the savings from energy efficiency upgrades exceeds the amount saved by installing a smaller PV array, then there are two courses of action.

1. What other energy efficiency upgrades are available? Compare the total costs and savings with the previous analysis.

2. If all energy efficiency options have been considered, install the PV array first.

In some cases, it may not be feasible to increase energy efficiency or install PV from a purely economic point of view.

The major limitation of this method is that it requires detailed and accurate solar radiation and building demand information. This simulation relied on TMY3 weather data that do not account for the effect of the building's surroundings. Building demand is very dependent on occupant behavior and could vary drastically from year to year. It is also possible that actual solar data will include more variation from year to year than the TMY3 data. The major benefit of this technique is that it can be used to provide general data for a specific location based on building type. All three building types demonstrated similar results of different magnitude.

4.6 Conclusions and Future Work

From the analysis presented in this chapter, it is clear that using solar PV to reduce a building's CO_2 emissions is effective, but not economical for the selected models. Improvements in the manufacturing process could lead to reduced costs and CO_2 emissions associated with PV.

A further analysis of the calculation of the LCOE for PV technology would yield a deeper understanding of the economic results. This information could be combined with Rocky Mountain Power's Utah Rate Increase Projections [65] to estimate when PV will become a viable alternative source of electricity. Additional research into policy measures such as carbon taxes, tax breaks for renewable energy, etc. will improve the understanding of the economic analysis and allow a direct comparison between emissions and costs. This would also yield further insight into the potential to use distributed PV and energy storage systems to provide peak shaving for the electricity grid.

Besides additional economic analysis, there are many possibilities for future research that would improve the quality of results obtained through the demand matching method. Additional code (newton.m and solar.m) is included in Appendix B to solve for array angle and recommended size simultaneously using Newton's optimization method [66]. A sensitivity analysis would be useful to determine the minimum amount of solar radiation and building demand data are required to obtain accurate results. The current solar model neglects the effect of the solar azimuth angle, which could be incorporated in a manner similar to the optimal solar altitude angle. Beyond improving the solar model, the optimal sizing could be expanded to include other forms of site-specific energy generation technology such as wind turbines, or combined heat and power. As discussed in Chapter 3, these methods could be applied to a model building on the University of Utah campus. This would require the collection of solar radiation and building demand data, and the validation of the building model. These expanded models could also include the interactions between neighboring buildings.

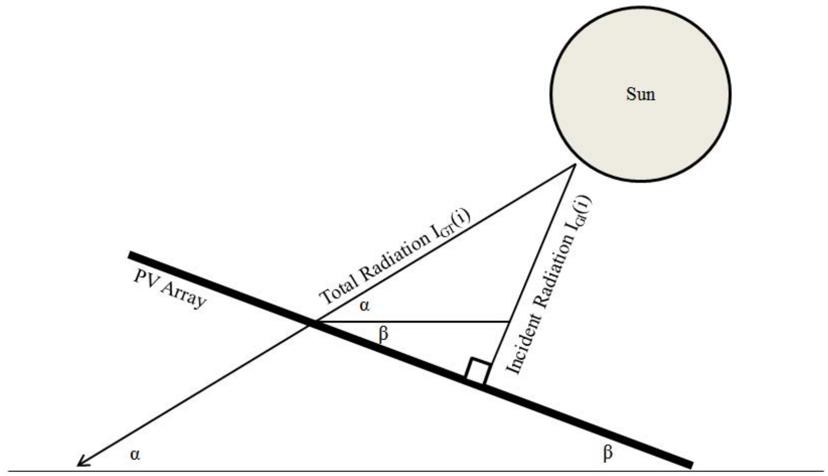

Figure 4.1. Solar radiation incident on an angled PV array

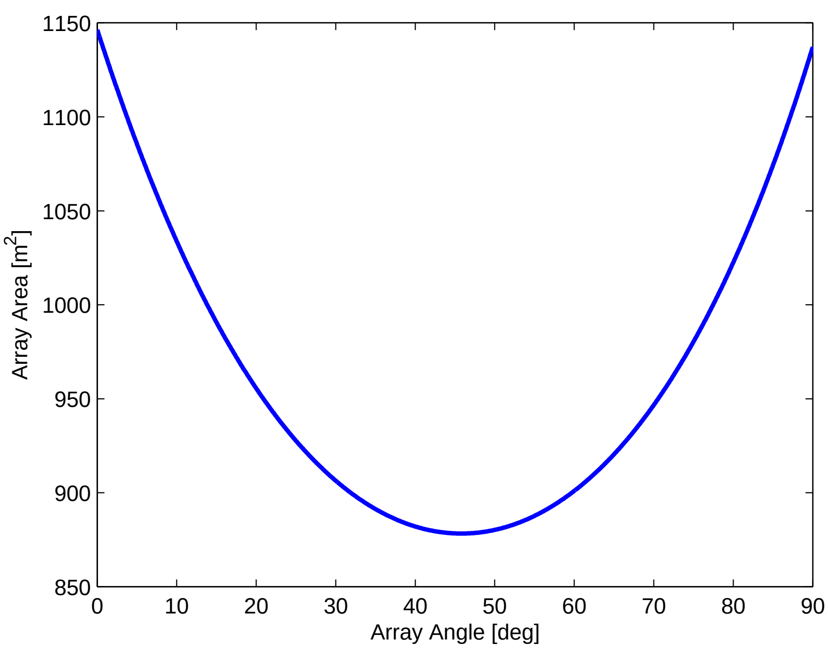

Figure 4.2. Results of the trial and error technique for the medium office without energy efficiency upgrades

Table 4.1. PV array sizing parameters

PV panel efficiency [67]	[%]	15.00
Inverter efficiency [68]	[%]	95.00
Electricity rate [64]	[$/kWh]	0.0819
Surplus rate [49]	[$/kWh]	0.0277
PV LCOE [48]	[$/kWh]	0.1400
CO_2 emissions factor [60]	[kg/kWh]	0.6000
CO_2 emissions minimum [60]	[kg/kWh]	0.2000
PV CO_2 emissions factor [69]	[kg/kWh]	0.0700

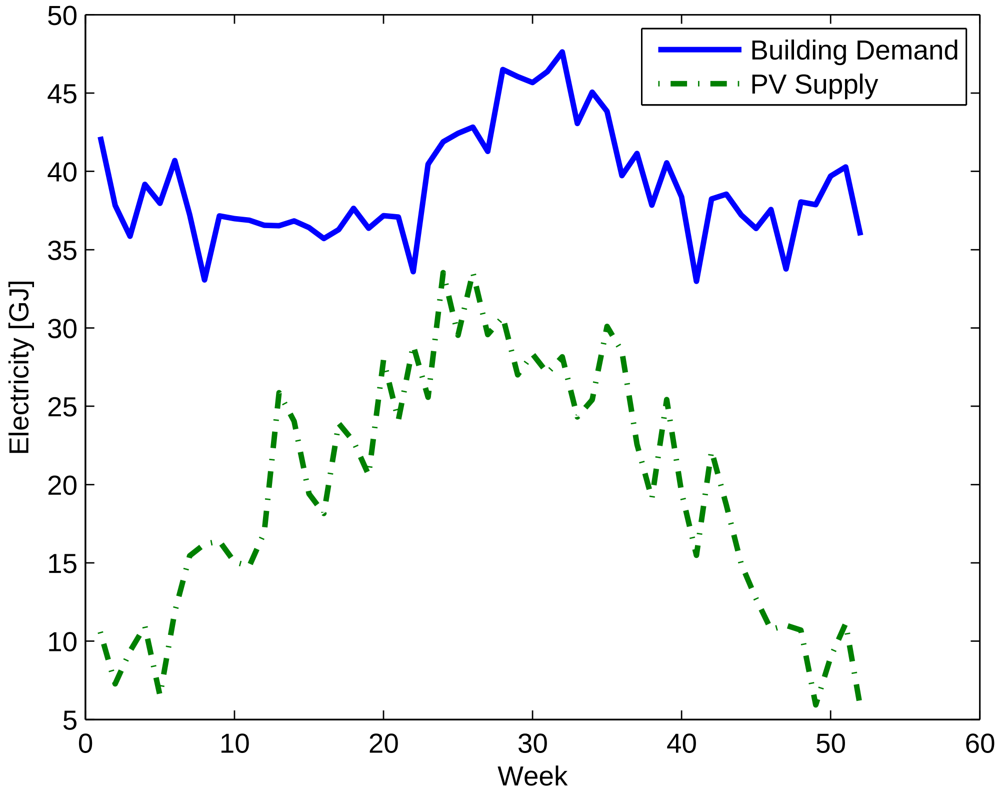

Figure 4.3. Demand matching data for the improved medium office building summed by week

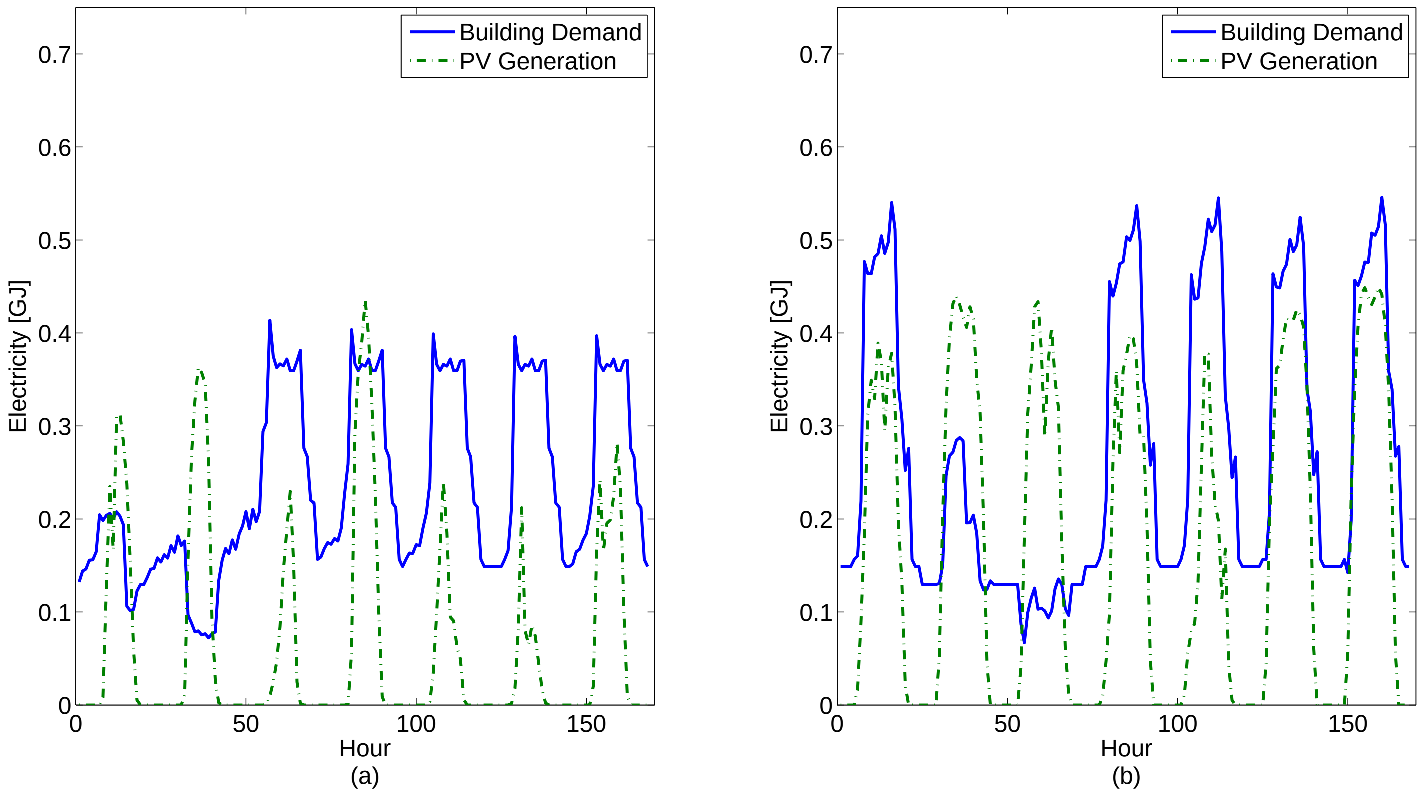

Figure 4.4. Hourly demand matching data for the improved medium office building. (a) shows data beginning on Saturday, January 21st, while (b) shows data beginning on Friday, July 21st.

Table 4.2. PV array sizing summary and baseline data (+ indicates the building is equipped with the efficiency upgrades detailed in Chapter 3)

Baseline	**Demand [GJ]**			
Medium Office	3171.26			
Primary School	3725.21			
Supermarket	7096.32			
PV Array	**Angle [deg]**	**Area [m^2]**	**Demand [GJ]**	**Surplus [GJ]**
Medium Office	45.31	1360.43	1877.50	293.36
Medium Office+	45.87	878.28	1193.09	182.96
Primary School	45.03	1638.78	2193.34	379.17
Primary School+	44.24	1040.00	1570.77	233.29
Supermarket	45.42	3096.58	3849.92	366.94
Supermarket+	45.31	2257.63	3083.53	266.66

Table 4.3. Cost and emissions results summary with installed PV

Baseline	**Operating Cost [$]**	**Emissions [kg]**
Medium Office	132,426.71	528,542.86
Primary School	140,116.35	620,868.07
Supermarket	228,544.24	1,182,719.64
PV Array	**Operating Cost [$]**	**Emissions [kg]**
Medium Office	157,686.26	343,776.78
Medium Office+	91,591.50	218,793.76
Primary School	166,977.55	402,760.38
Primary School+	109,158.48	285,330.69
Supermarket	293,424.41	711,912.84
Supermarket+	221,329.60	565,134.89

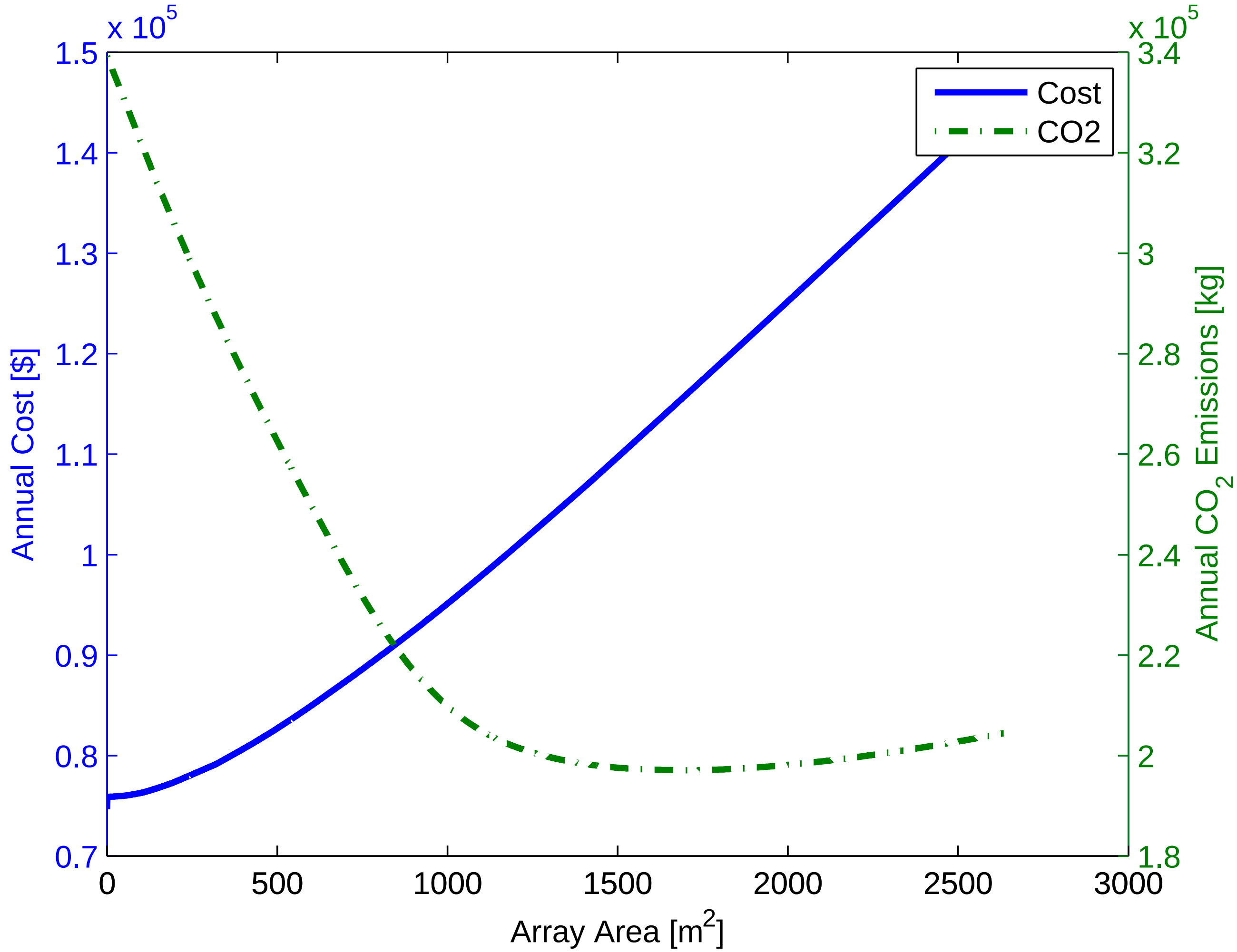

Figure 4.5. The trade off between the array area, annual cost, and CO_2 emissions is displayed for the medium office building. For reference, the recommended size is 878 m^2. The roof area is 1,660 m^2.

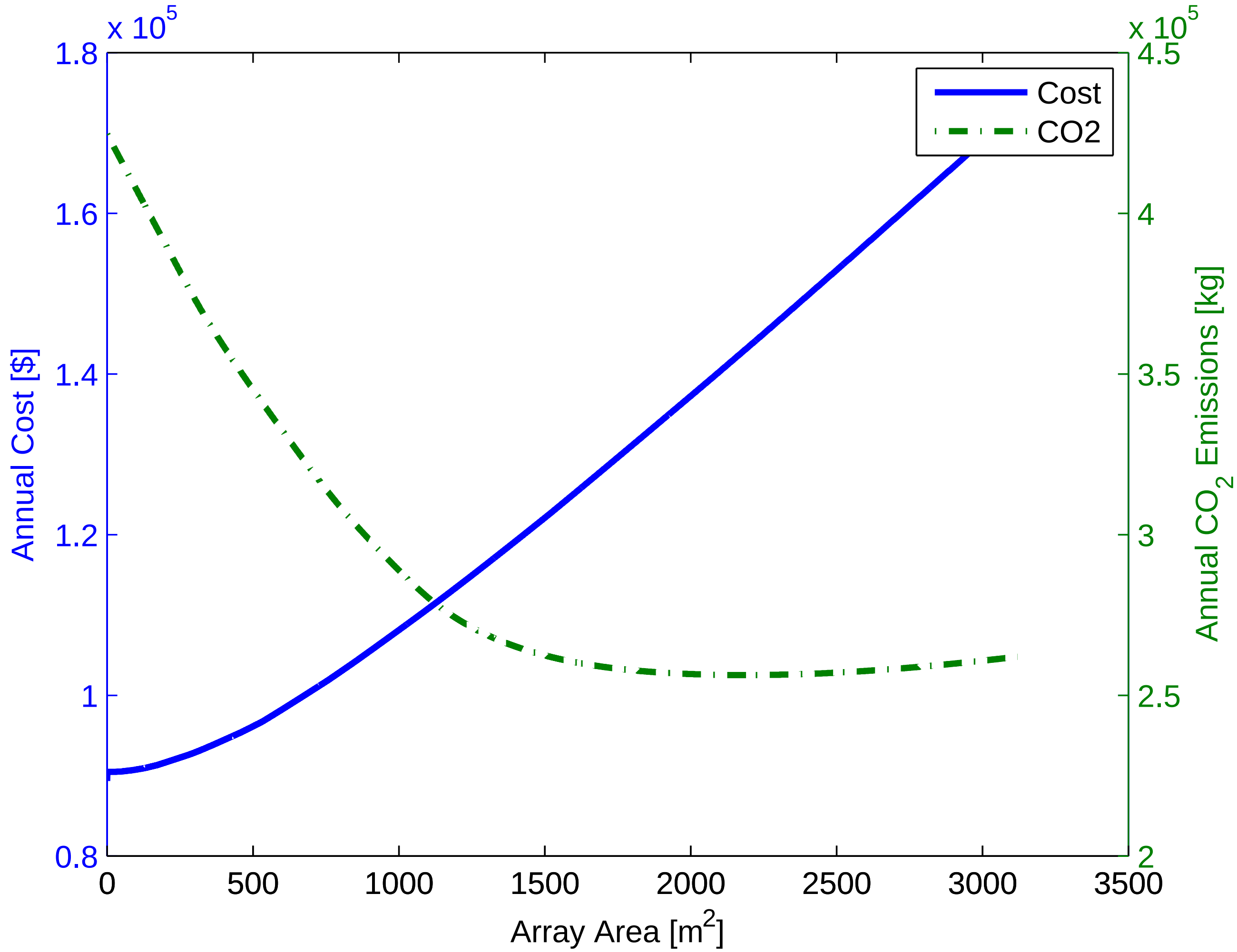

Figure 4.6. The trade off between the array area, annual cost, and CO_2 emissions is displayed for the primary school. For reference, the recommended size is 1040 m^2. The roof area is 6,871 m^2.

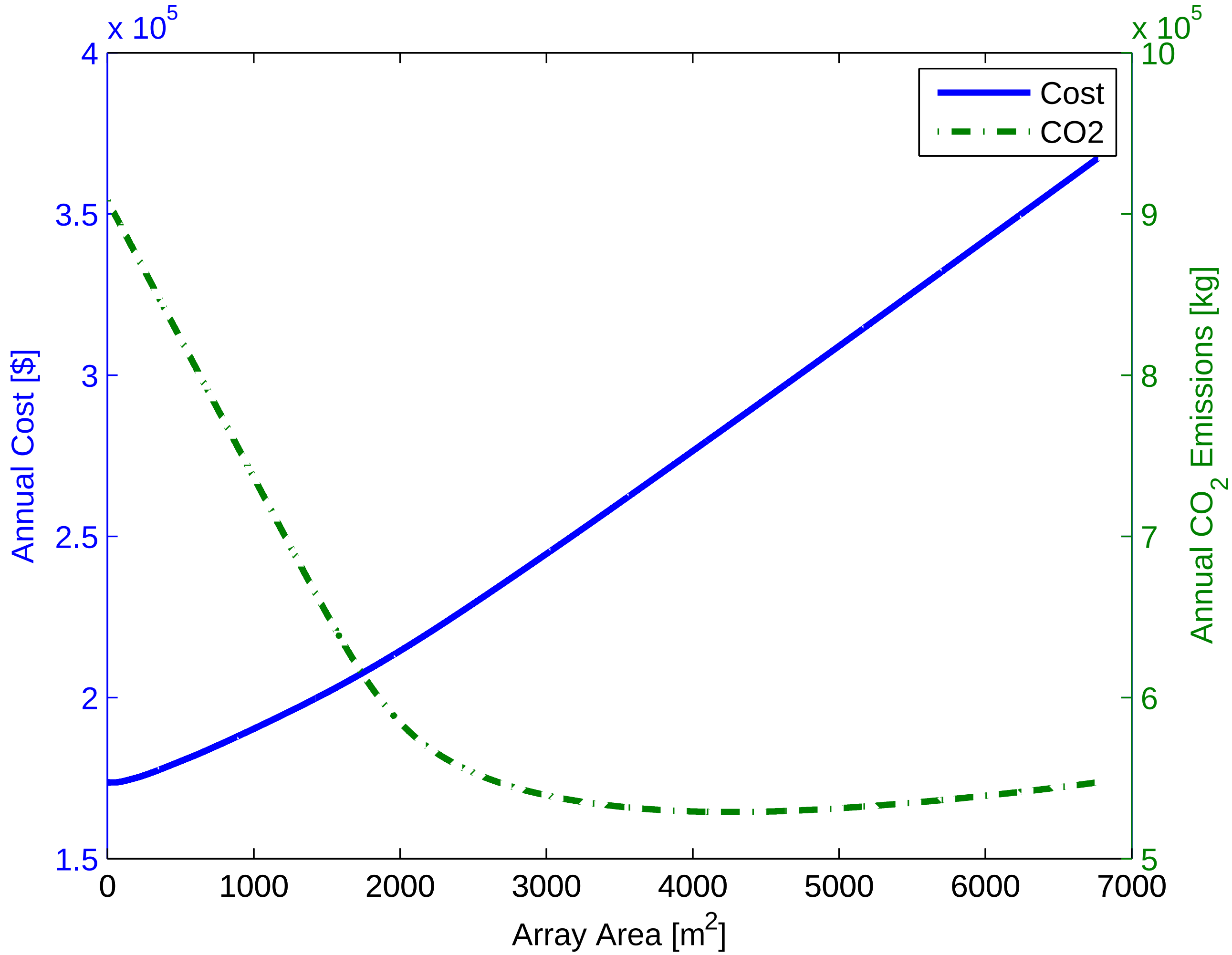

Figure 4.7. The trade off between the array area, annual cost, and CO_2 emissions is displayed for the supermarket. For reference, the recommended size is 2257 m^2. The roof area is 4,180 m^2.

CHAPTER 5

CONCLUSIONS AND FUTURE WORK

Results from both energy efficiency and PV simulations were shown to decrease the total source CO_2 emissions (Table 5.1). Note, the combined total for energy efficiency upgrades is from the results of a simulation including these upgrades. It is not equal to the sum of the individual upgrades. This indicates that the efficiency upgrades can influence each other, and should be simulated together for the most accurate results. The largest reduction in CO_2 emissions includes all the energy efficiency upgrades from Chapter 3, as well as a PV array sized using the demand matching method in Chapter 4. It was determined that a PV installation is not feasible from an entirely economic point of view. However, from Figures 4.5, 4.6, and 4.7, there is one interesting trend between cost and CO_2 emissions for all three buildings. On the far left of these plots, cost does not increase as steeply as it does further to the right. The slight increase in total cost corresponds to a much larger increase in CO_2 emissions. This indicates that a case could be made for small-scale solar arrays in Salt Lake City, especially with a policy incentive to encourage the installation of building PV arrays.

The research presented in this thesis contains many opportunities for improvement and expansion. As outlined in Chapter 3, one of the major limitations of the energy efficiency simulations is the lack of specific economic data. One possible solution would be to create EnergyPlus models for specific buildings in Salt Lake City. Several of the newer buildings on the University of Utah campus collect detailed energy consumption data. One major advantage of modeling a building on the university campus is that it could be validated against actual consumption data. With detailed information on a real building, it would be possible to work with local construction companies to accurately estimate the costs associated with energy efficiency upgrades.

An alternative direction of research could focus on obtaining a deeper understanding of why some efficiency upgrades were more successful for one model than another. More specifically, why was the reduction in CO_2 emissions associated with insulation so small for all three buildings? Or why was the window U-factor less successful for the primary school than it was for the medium office building? Additionally, the interaction between efficiency upgrades could be examined. From Table 5.1, it is clear that the combined total emissions is less than the sum of the individual upgrades. This approach could include the addition of more efficiency upgrades to determine what combinations work best for a given commercial reference model. Furthermore, the commercial reference models could be used to create a profile of the building stock in Salt Lake City. This would be useful to estimate the achievable reduction in local emissions.

Similar to the efficiency upgrades, the optimal solar sizing could be simulated for a building on the university's campus. Several buildings on campus already collect solar radiation data and these could be used to make a comparison between local data, and TMY3 data. Its likely that local data would demonstrate more variation than the TMY3 data that were collected and averaged over 30 years. Moreover, the optimization could be expanded to include solar azimuth angle, solar tracking, or the combination of several forms of site-specific energy generation. It may also be possible to simplify the current demand matching algorithm using a sensitivity analysis. Currently, it is not known how much data are required to obtain accurate results. If less data are required, not only would this improve the speed of the simulation, but the method would become more available to those without a scientific or research background.

Table 5.1. Summary of CO_2 reductions resulting from energy efficiency measures and PV array installation (+ indicates the simulation includes all energy efficiency upgrades)

Energy Efficiency	**Medium Office**	**Primary School**	**Supermarket**
Lighting Intensity [%]	14.0	22.7	8.7
Temperature Setpoint [%]	15.7	10.4	16.6
Insulation R-value [%]	3.6	2.8	2.6
Window U-factor [%]	6.2	1.1	0.5
Combined Total [%]	35.8	31.6	23.2

PV Installation	**Medium Office**	**Primary School**	**Supermarket**
Optimal Area [%]	35.0	35.1	40.0

PV Installation	**Medium Office+**	**Primary School+**	**Supermarket+**
Optimal Area [%]	58.6	54.0	52.2

APPENDIX A

MODEL FLOOR PLANS

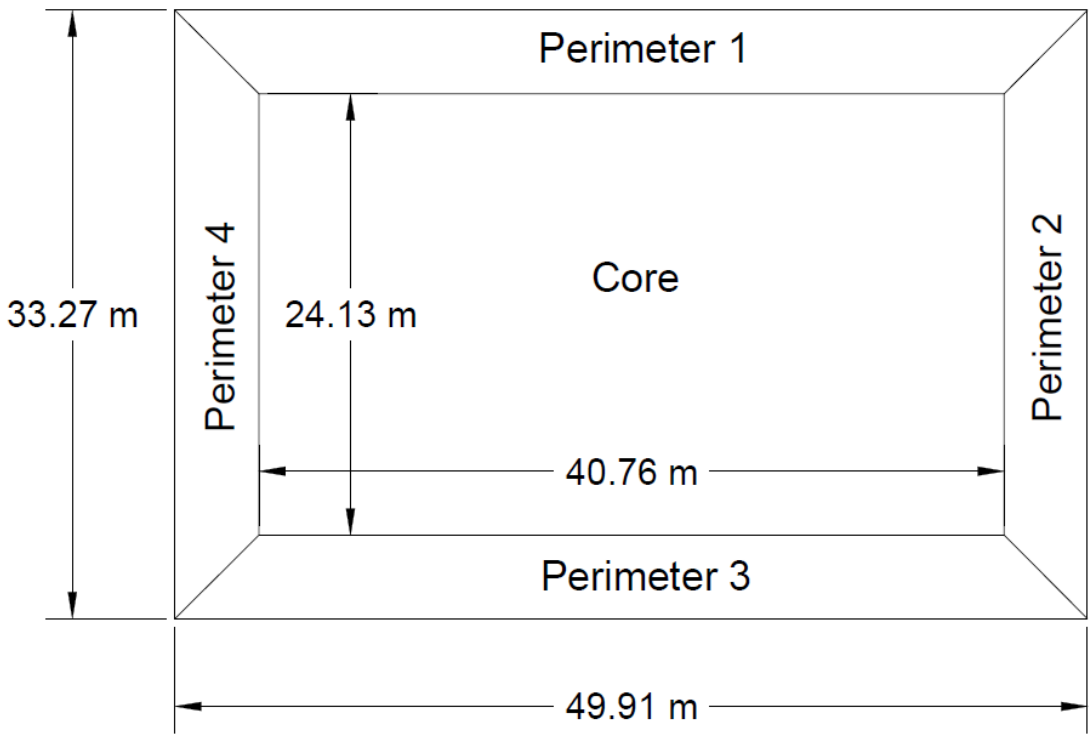

Figure A.1. Medium office commercial reference model floor plan (all units are meters)

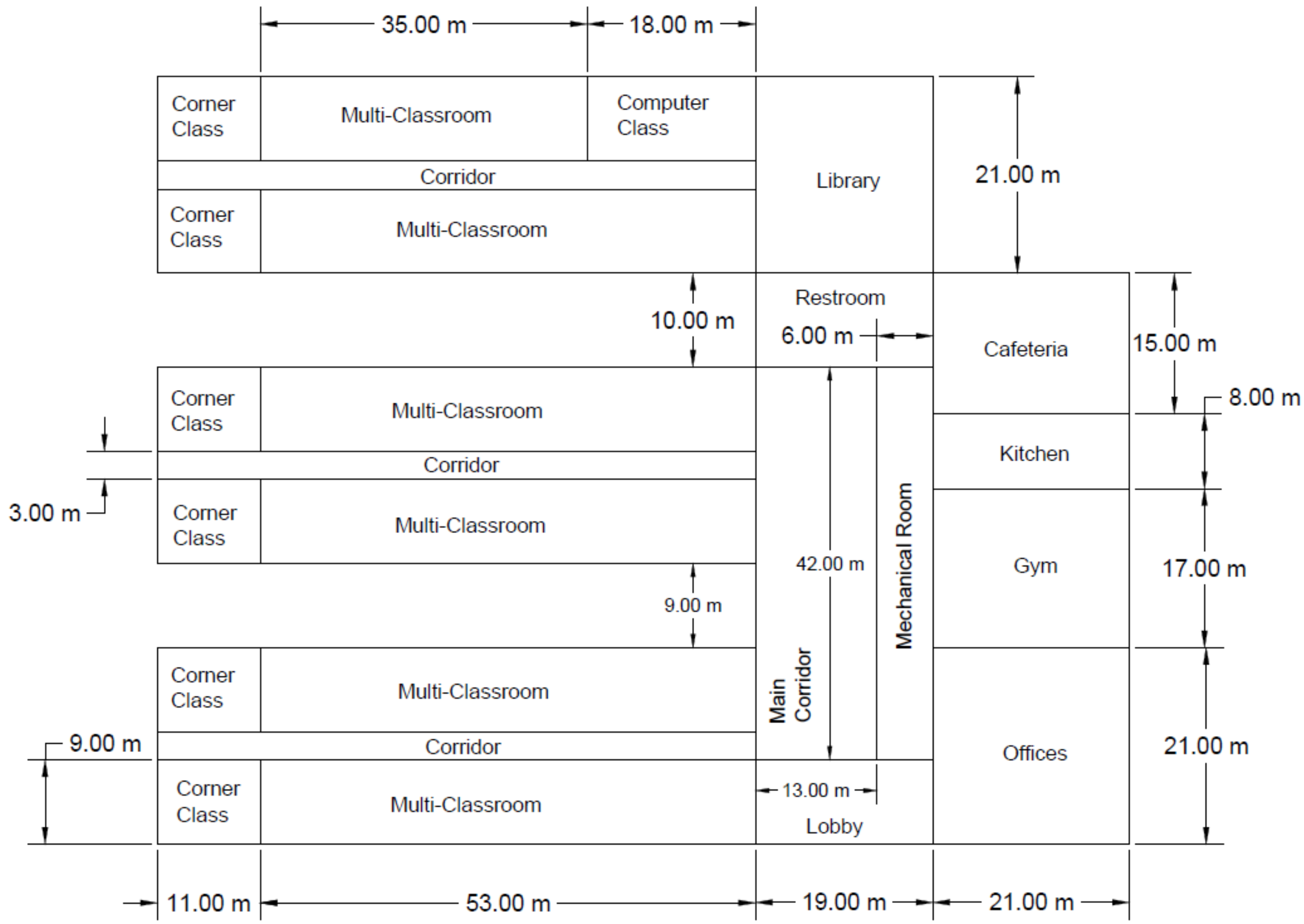

Figure A.2. Primary school commercial reference model floor plan (all units are meters)

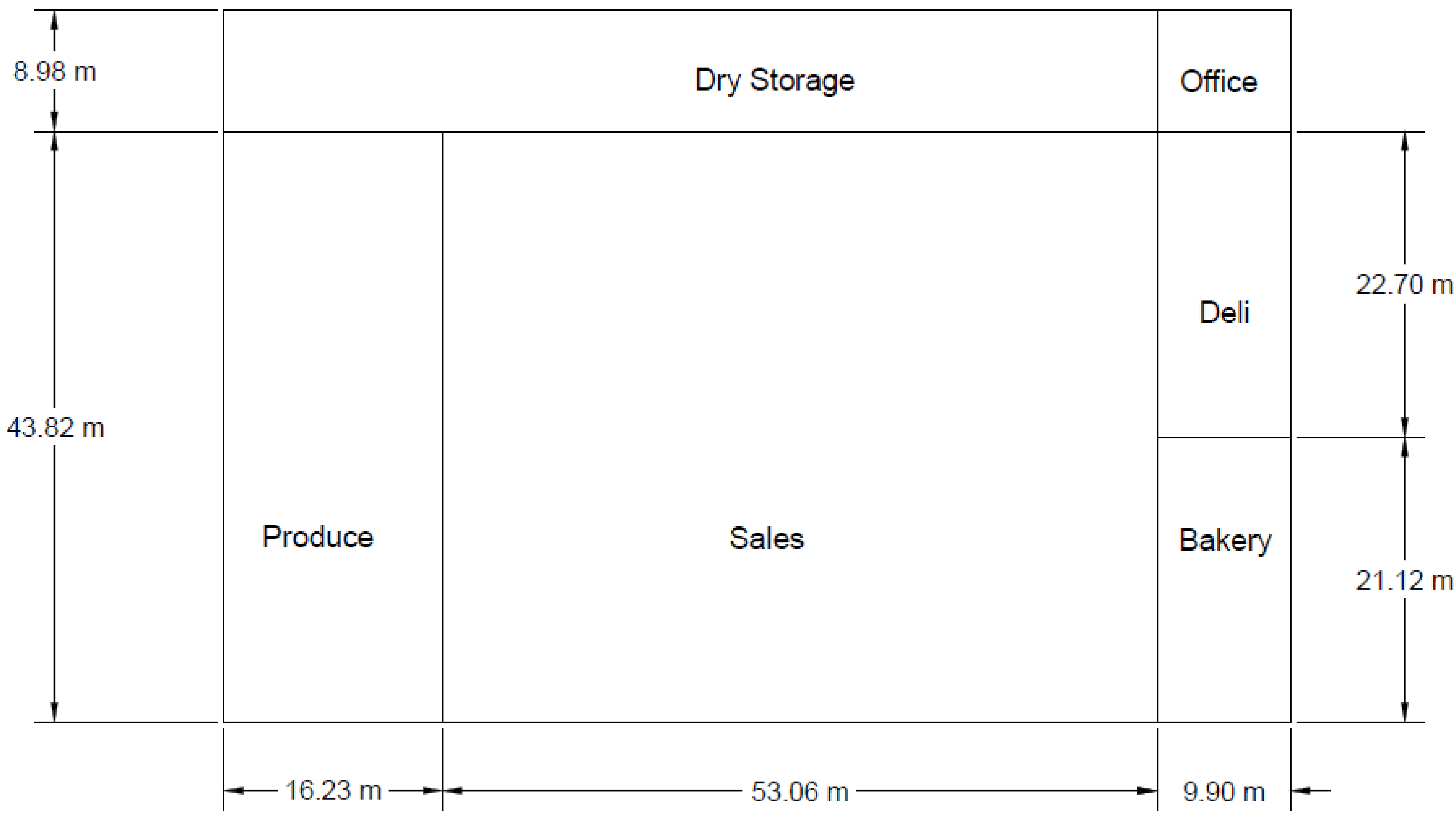

Figure A.3. Supermarket commercial reference model floor plan (all units are meters)

APPENDIX B

MATLAB CODE

```
% Golden Section Search Algorith Script
function [As,Angle_opt,t,i] = GoldenSearch(a0L,a0u,SLC,params)
tic;
d = (sqrt(5)-1)/2*(a0u-a0L);
a01 = a0L+d;
a02 = a0u-d;
yp1 = SaMatch(a01,SLC,params);
yp2 = SaMatch(a02,SLC,params);
i = 1;
e = 1;
while e > 0.01
    if yp1 < yp2
        aopt = a01;
        a0L = a02;
        a02 = a01;
        yp2 = yp1;
        d = (sqrt(5)-1)/2*(a0u-a0L);
        a01 = a0L+d;
        yp1 = SaMatch(a01,SLC,params);
    else
        aopt = a02;
        a0u = a01;
        a01 = a02;
        yp1 = yp2;
        d = (sqrt(5)-1)/2*(a0u-a0L);
        a02 = a0u-d;
        yp2 = SaMatch(a02,SLC,params);
    end
e = abs((a0u-a0L)/aopt);
A(i) = aopt;
i = i+1;
end
As = min(yp1,yp2);
Angle_opt = A(i-1);
t = toc;
```

```
% Solar Array Sizing
function [As] = SaMatch(alpha,SLC,params)
% component efficiencies & parameters
x = params(1);              % surplus penalty
y = params(2);              % emissions penalty
PV_angle = alpha;           % array angle [deg]
% incident radiation on angled array
SLC(:,6) = SLC(:,6).*sind(SLC(:,5)+PV_angle);
% Sizing Code
As = (SLC(:,6)'*SLC(:,6))^-1*(SLC(:,6)'*SLC(:,7));

% penalty terms
for i = 1:length(SLC)
    if SLC(i,3) < (As*SLC(i,6))
        data_F(i,4) = SLC(i,6)*x;
    elseif SLC(i,3) > (As*SLC(i,6))
        data_F(i,4) = SLC(i,6)*y;
    end
end
As = (data_F(:,4)'*data_F(:,4))^-1*(data_F(:,4)'*SLC(:,7));

return
```

```
function [x,fun,i,vax,error] = newton(x,f,SLC)
vax(1,1) = x(1);
vax(1,2) = x(2);
i = 1;
error = 1;
while error > 0.001
    [fun,g,H] = f(x,SLC);
    p = -H\g;
    x = x+p;
    vax(i+1,1) = x(1);
    vax(i+1,2) = x(2);
    if (abs(vax(i+1,1)-vax(i,1))) > (abs(vax(i+1,2)-vax(i,2)))
        error(i,1) = (abs(vax(i+1,1)-vax(i,1)));
    else
        error(i,1) = (abs(vax(i+1,2)-vax(i,2)));
    end
    i = i+1;
end
```

```
function [fun,g,H] = solar(x0,SLC)
As = x0(1,1);
beta = x0(2,1);
a = SLC(:,6);
b = SLC(:,7);
alpha = SLC(:,5);
fun = sum((b-As*sind(alpha+beta).*a).^2);
% derivatives
fx = sum(-2*a.*sind(alpha+beta).*(b-As*a.*sind(alpha+beta)));
fy = sum(-2*As*a.*cosd(alpha+beta).*(b-As*a.*sind(alpha+beta)));
% second derivatives
fxx = sum(2*a.^2.*sind(alpha+beta).^2);
fxy = sum(2*As*a.^2.*cosd(alpha+beta).*sind(alpha+beta)-2*...
    a.*cosd(alpha+beta).*(b-As*a.*sind(alpha+beta)));
fyy = sum(2*As^2*a.^2.*cosd(alpha+beta).^2+2*As*a.*...
    sind(alpha+beta).*(b-As*a.*sind(alpha+beta)));
fyx = sum(2*As*a.^2.*cosd(alpha+beta).*sind(alpha+beta)-2*...
    a.*cosd(alpha+beta).*(b-As*a.*sind(alpha+beta)));
if (nargout>=2)
    g(1,1) = fx;
    g(2,1) = fy;
    if (nargout>=3)
        H(1,1) = fxx;
        H(1,2) = fxy;
        H(2,1) = fyx;
        H(2,2) = fyy;
    end
end
```

REFERENCES

[1] Kelso, J. D., ed., 2012. *2011 Buildings Energy Data Book.* U.S. Department of Energy.

[2] U.S. Energy Information Administration, 2014. *U.S. Energy-Related Carbon Dioxide Emissions, 2013.* U.S. Department of Energy.

[3] Çengel, Y. A., and Boles, M. A., 2011. *Thermodynamics - An Engineering Approach*, 7th ed. McGraw Hill, ch. Chemical Reactions, pp. 767–812.

[4] Tester, J. W., Drake, E. M., Driscoll, M. J., Golay, M. W., and Peters, W. A., 2012. *Sustainable Energy - Choosing Among Options*, 2nd ed. The MIT Press, Cambridge, Massachusetts.

[5] Petersen, J. E., Shunturov, V., Janda, K., Platt, G., and Weinberger, K., 2007. "Dormitory residents reduce electricity consumption when exposed to real-time visual feedback and incentives". *International Journal of Sustainability in Higher Education,* ***8***(1), pp. 16–33.

[6] Manwell, J., McGowan, J., and Rogers, A., 2009. *Wind Energy Explained - Theory, Design and Applications*, 2nd ed. Wiley.

[7] Tsoutsos, T., Frantzeskaki, N., and Gekas, V., 2005. "Environmental impacts from the solar energy technologies". *Energy Policy,* ***33***(3), pp. 289–296.

[8] Chu, S., 2010. "Energy Efficiency: Achieving the Potential". *Energy Vision Update 2010: Towards a More Energy Efficient World*, p. 14.

[9] The National Research Council, 2009. *America's Energy Future: Technology and Transformation.* The National Academy of Sciences.

[10] Granade, H. C., Creyts, J., Derkach, A., Farese, P., Nyquist, S., and Ostrowski, K., 2009. *Unlocking Energy Efficiency in the U.S. Economy.* McKinsey & Company.

[11] Kneifel, J., 2010. "Life-cycle carbon and cost analysis of energy efficiency measures in new commercial buildings". *Energy and Buidings,* ***42***, pp. 333–340.

[12] Shellenberger, M., and Nordhaus, T., 2014. The Problem With Energy Efficiency. http://www.nytimes.com/2014/10/09/opinion/the-problem-with-energy-efficiency.html?smidñytcore-ipad-share&smprodñytcore-ipad&_r1̄.

[13] Heberlein, T. A., 2012. *Changing Environmental Attitudes.* Oxford University Press.

[14] EnergyPlus, U.S. Department of Energy, 2012., October. Version 7.2.

[15] U.S. Department of Energy, 2014. Commercial reference buildings. http://energy.gov/eere/buildings/commercial-reference-buildings.

[16] U.S. Department of Energy, 2014. Weather data for simulation. http://apps1.eere.energy.gov/buildings/energyplus/weatherdata_simulation.cfm.

[17] U.S. Energy Information Administration, 2014. U.S. States. http://www.eia.gov/.

[18] Weisser, D., 2007. "A guide to life-cycle greenhouse gas (ghg)emissions from electric supply technologies". *Energy,* ***32***, pp. 1543–1559.

[19] Varun, Bhat, I., and Prakash, R., 2009. "LCA of renewable energy for electricity generation systems - A review". *Renewable and Sustainable Energy Reviews,* ***13***, pp. 1067–1073.

[20] U.S. Energy Information Administration, 2014. State-level energy-related carbon dioxide emissions, 2000-2011. http://www.eia.gov/environment/emissions/state/analysis/.

[21] Deru, M., and Torcellini, P., 2007. Source Energy and Emission Factors for Energy Use in Buildings. Tech. Rep. NREL/TP-550-38617, National Renewable Energy Laboratory.

[22] Lawrence Berkeley National Laboratory, 2013. *Getting Started with EnergyPlus.* U.S. Department of Energy.

[23] Oh, S., 2013. "Origins of Analysis Methods in Energy Simulation Programs Used for High Performance Commercial Buildings". Master's thesis, Texas A&M University, August.

[24] Lawrence Berkeley National Laboratory, 2013. *EnergyPlus Engineering Reference.* U.S. Department of Energy.

[25] Wilcox, S., and Marion, W., 2008. Users Manual for TMY3 Data Sets. Tech. Rep. NREL/TP-581-43156, National Renewable Energy Laboratory.

[26] Deru, M., Field, K., Studer, D., Benne, K., Griffith, B., Torcellini, P., Liu, B., Halverson, M., Winiarski, D., Rosenberg, M., et al., 2011. U.S. Department of Energy commercial reference building models of the national building stock. Tech. Rep. NREL/TP-5500-46861, National Renewable Energy Laboratory.

[27] U.S. Energy Information Administration, 2013. Commercial Buildings Energy Consumption Survey. http://www.eia.gov/consumption/commercial/about.cfm.

[28] Field, K., Deru, M., and Studer, D., 2010. Using DOE Commercial Reference Buildings for Simulation Studies. Tech. Rep. NREL/CP-550-48588, National Renewable Energy Laboratory.

[29] Torcellini, P., Deru, M., Griffith, B., and Benne, K., 2008. DOE Commercial Building Benchmark Models. Tech. Rep. NREL/CP-550-43291, National Renewable Energy Laboratory.

[30] Judkoff, R., and Neymark, J., 2006. "Model Validation and Testing: The Methodological Foundation of ASHRAE Standard 140". *ASHRAE Transactions,* ***112***.

[31] Judkoff, R., Wortman, D., O'Doherty, B., and Burch, J., 2008. A methodology for validating building energy analysis simulations. Tech. Rep. SERI/TR-254-1508, Solar Energy Research Institute.

[32] ASHRAE, 2009. *ASHRAE Handbook - Fundamentals.* American Society of Heating, Refrigeration, and Air Conditioning Engineers, ch. 19 - Energy Estimating and Modeling Methods - Model Validation and Testing, pp. 31–33.

[33] The American Society of Heating, Refrigeration, and Air Conditioning Engineers, 2014. Advanced Energy Design Guides. http://www.ashrae.org.

[34] Darby, S., 2001. *Energy Efficiency in Household Appliances and Lighting.* Springer Berlin Heidelberg, ch. Making it Obvious: Designing Feedback into Energy Consumption, pp. 685–696.

[35] Winward, J., Schiellerup, P., and Boardman, B., 1998. *Cool Labels: the first three years of the European Energy Label.* Energy and Environmental Programme, Environmental Change Unit, University of Oxford.

[36] Weiss, M., Mattern, F., Graml, T., Staake, T., and Fleisch, E., 2009. "Handy feedback: Connecting smart meters with mobile phones". In Proceedings of the 8th International Conference on Mobile and Ubiquitous Multimedia.

[37] Frank Kreith, S. K., and Kreider, J. F., 2010. *Priciples of Sustainable Energy.* CRC Press.

[38] Solar Simplified, 2014. Salt Lake Solar Map. http://solarsimplified.org/solar-resources/solar-map.

[39] National Renewable Energy Laboratory, 2013. Solar Maps. http://www.nrel.gov/gis/solar.html.

[40] Fthenakis, V., and Kim, H. C., 2010. "Life-cycle uses of water in U.S. electricity generation". *Renewable and Sustainable Energy Reviews,* ***14***, pp. 2039–2048.

[41] Kreith, F., and Kreider, J. F., 1978. *Principles of Solar Engineering.* Hemisphere Publishing Corp.

[42] Darling, S. B., You, F., Veselka, T., and Velosa, A., 2011. "Assumptions and the levelized cost of energy for photovoltaics". *Energy and Environmental Science.*

[43] Branker, K., Pathak, M., and Pearce, J., 2011. "A review of solar photovoltaic levelized cost of electricity". *Renewable and Sustainable Energy Reviews,* ***15***, pp. 4470–4482.

[44] Park, S., Wang, Y., Kim, Y., Chang, N., and Pedram, M., 2012. "Battery management for grid-connected PV systems with a battery". In Proceedings of the 2012 ACM/IEEE international symposium on low power electronics and design, ACM/IEEE.

[45] Shear, T., 2014. Peak-to-average electricity demand ratio rising in New England and many other U.S. regions, U.S. Energy Information Administration. http://www.eia.gov/todayinenergy/detail.cfm?id$\bar{1}$5051#tabs_SpotPriceSlider-6.

[46] U.S. Energy Information Administration, 2013. Electricity demand patterns matter for valuing electricity supply resources. http://www.eia.gov/todayinenergy/detail.cfm?id$\bar{1}$2711#.

[47] Booth, W., 2013. Variability in electricity demand highlights potential roles for electricity storage, U.S. Energy Information Administration. http://www.eia.gov/todayinenergy/detail.cfm?id$\bar{1}$3131.

[48] U.S. Energy Information Administration, 2012. Annual energy outlook 2013, December. DOE/EIA-0383(2012).

[49] Rocky Mountain Power, 2014. Utah Regulatory Information. https://www.rockymountainpower.net/about/rar/uri.html.

[50] Salas, V., Olías, E., Barrado, A., and Lázaro, A., 2006. "Review of the maximum power point tracking algorithms for stand-alone photovoltaic systems". *Solar Energy Materials and Solar Cells,* ***90***, pp. 1555–1578.

[51] Arun, P., Banerjee, R., and Bandyopadhyay, S., 2007. "Sizing curve for design of isolated power systems". *Energy for Sustainable Development,* ***XI***(4), pp. 21–28.

[52] Arun, P., Banerjee, R., and Bandyopadhyay, S., 2009. "Optimum sizing of photovoltaic battery systems incorporating uncertainty through design space approach". *Solar Energy,* ***83***, pp. 1013–1025.

[53] Baños, R., Manzano-Agugliaro, F., Montoya, F., Gil, C., Alcayde, A., and Gómez, J., 2011. "Optimization methods applied to renewable and sustainable energy: A review". *Renewable and Sustainable Energy Reviews,* ***15***, pp. 1753–1766.

[54] Khatib, T., Mohamed, A., and Sopian, K., 2013. "A review of photovoltaic system size optimization techniques". *Renewable and Sustainable Energy Reviews,* ***22***, pp. 454–465.

[55] Mellit, A., Kalogirou, S., Hontoria, L., and Shaari, S., 2009. "Artificial intelligence techniques for sizing photovoltaic systems: a review". *Renewable and Sustainable Energy Reviews,* ***13***, pp. 406–419.

[56] Toledo, O. M., Filho, D. O., and Diniz, A. S. A. C., 2010. "Distributed photovoltaic generation and energy storage systems: a review". *Renewable and Sustainable Energy Reviews,* ***14***, pp. 506–511.

[57] Erdinc, O., and Uzungoglu, M., 2012. "Optimum design of hybrid renewable energy systems: Overview of different approaches". *Renewable and Sustainable Energy Reviews,* ***16***, pp. 1412–1425.

[58] Lucich, S., and Smith, A., 2014. "Estimating CO_2 Emissions Reductions with EnergyPlus for and Office Building in Salt Lake City". In Proceedings of the ASME 2014 8th Internation Conference on Energy Sustainability & 12th Fuel Cell Science, Engineering and Technology Conference.

[59] Khedari, J., Yamtraipat, N., Pratintong, N., and Hirunlabh, J., 2000. "Thailand ventilation comfort chart". *Energy and Buildings,* ***32***, pp. 245–249.

[60] Environmental Protection Agency, 2010. *Year 2009 EGRID Subregion Emissions - Greenhouse Gases.*

[61] Environmental Protection Agency, 2008. *Direct Emissions from Stationary Combustion Sources.*

[62] Borowy, B. S., and Salameh, Z. M., 1994. "Optimum Photovoltaic Array Size for a Hybrid Wind/PV System". In IEEE Transactions on Energy Conversion, Vol. 9, pp. 482–488.

[63] MathWorks, 2012. MATLAB. Student Version 2012a.

[64] Utah Geological Survey: Utah Department of Natural Resources, 2013. Utah energy and mineral statistics, October. http://geology.utah.gov.

[65] Rocky Mountain Power, 2014. Utah Rate Increase Projections. https://www.rockymountainpower.net/about/rar/rp/urip.html.

[66] Nocedal, J., 2000. *Numerical Optimization*, 2nd ed. Springer.

[67] Green, M. A., Emery, K., Hishikawa, Y., Warta, W., and Dunlop, E. D., 2014. "Solar cell efficiency tables (version 43)". *Progress in photovoltaics: research and applications,* ***22***(1), pp. 1–9.

[68] California Public Utilities Commission, Go Solar California, 2014. Inverter Performance Test Summaries. http://gosolarcalifornia.ca.gov.

[69] Union of Concerned Scientists, 2013. Environmental Impacts of Solar Power. http://www.ucsusa.org/clean_energy/our-energy-choices/renewable-energy/environmental-impacts-solar-power.html#.VLLs3yvF_jU.