CHALLENGES OF ACHIEVING ZERO ENERGY EDUCATION BUILDINGS

BY

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THESIS

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ABSTRACT

Buildings have significant impacts on the environment, economy, and society. Buildings account for 40% of the total energy consumption in the U.S. To improve the energy efficiency of buildings, the use of zero energy buildings (ZEB) has increased in recent years. The main objective of this research study is to investigate the challenges of attaining a zero energy education building by analyzing a case study of the Electrical and Computer Engineering (ECE) building at the University of Illinois at Urbana-Champaign. The ECE building was envisioned and planned to be the largest zero energy education building in the country and the world. Although the building has been in operation since 2015, it is still attempting to attain its zero energy goals and performance.

The objectives of this study are to (1) conduct a comprehensive literature review of the current practices and the latest research conducted on zero energy buildings; (2) evaluate the performance of a large education building, that was planned to be the largest ZEB in the U.S., as a case study, to analyze the challenges confronting its design and construction; (3) investigate the causes that prevented the analyzed case study from accomplishing its zero-energy goal and develop recommendations to enhance its current performance; and identify lessons learned that can be used to improve the design and construction of future similar ZEB.

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To my sister Dana Sourani

(May Her Soul Rest In Peace)

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CHAPTER 1 - INTRODUCTION

1.1 Overview

The U.S. was reported in 2018 to be the second highest country consuming energy in the world (Enerdata, 2018), as shown in Figure 1. The total annual consumption in the U.S. had been increasing in recent years, and its 2018 primary annual consumption reached 101.3 quadrillion British thermal unit (Btu) which was its highest on record, as shown in Figure 2. The U.S. Energy Information Administration (EIA) reported in 2019 that buildings accounted for 40% of the total energy consumption in the U.S. (EIA, 2019). Moreover, buildings account for 76% of the electricity consumption and 40% of all the carbon footprint (Global Alliance for Buildings and Construction, 2018). Buildings have a significant impact on the environment, economy, and society.

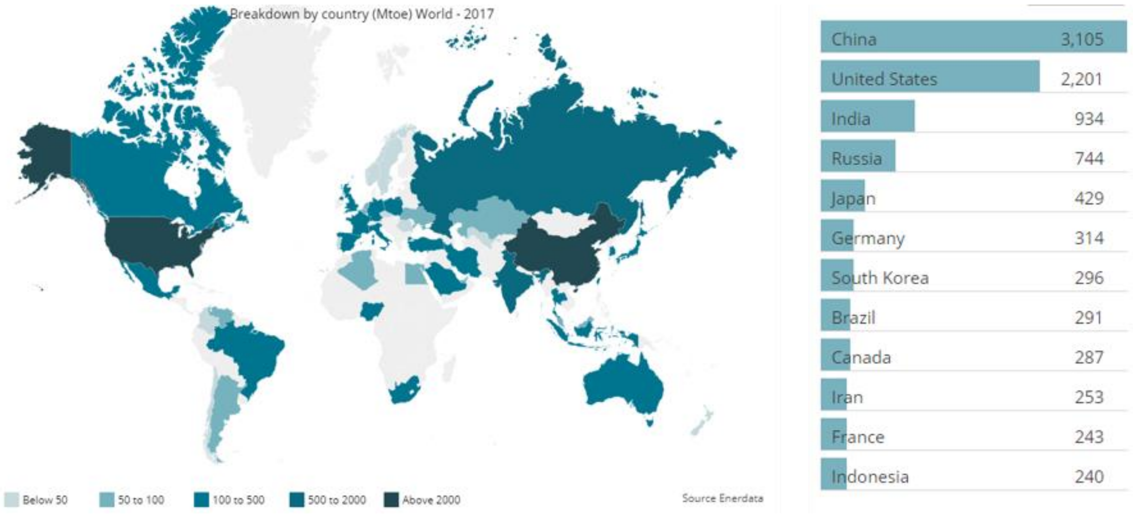


Figure 1: World energy consumption statistics, Enerdata 2017

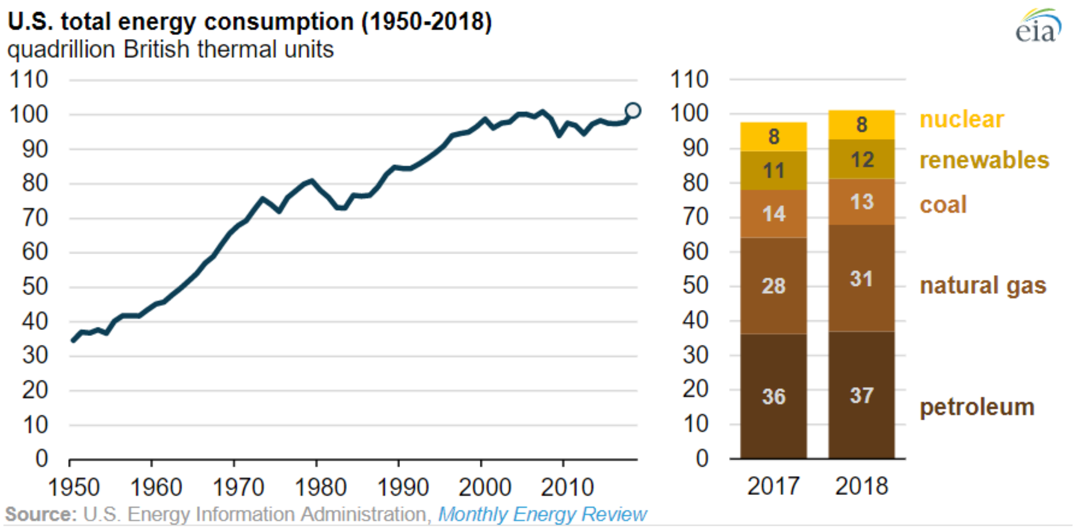


Figure 2: U.S. total energy consumption (1950-2018)

The global increase in energy consumption has raised awareness regarding building energy usage trends and energy conservation over the last few decades all over the world. Engineers, architects, and policymakers around the world have investigated ways of delivering highly efficient buildings with energy conservation capabilities while providing proper comfort conditions (Ionescu, Baracu, Vlad, Necula, & Badea, 2015). In 2011, the Building Performance Institute Europe (BPIE) conducted a survey to identify barriers to achieving building energy efficiency, as shown in Figure 3. These barriers included high initial costs, stakeholder's decision-making process, and awareness. To overcome these barriers, governments, utilities, and other organizations have been offering financial incentives to make energy efficiency more attainable for today's homes and businesses. For example, in Illinois, there are 131 programs including federal and state financial incentives such as tax credits, rebates, and savings programs, to promote and encourage energy efficient buildings (DOE, 2019).

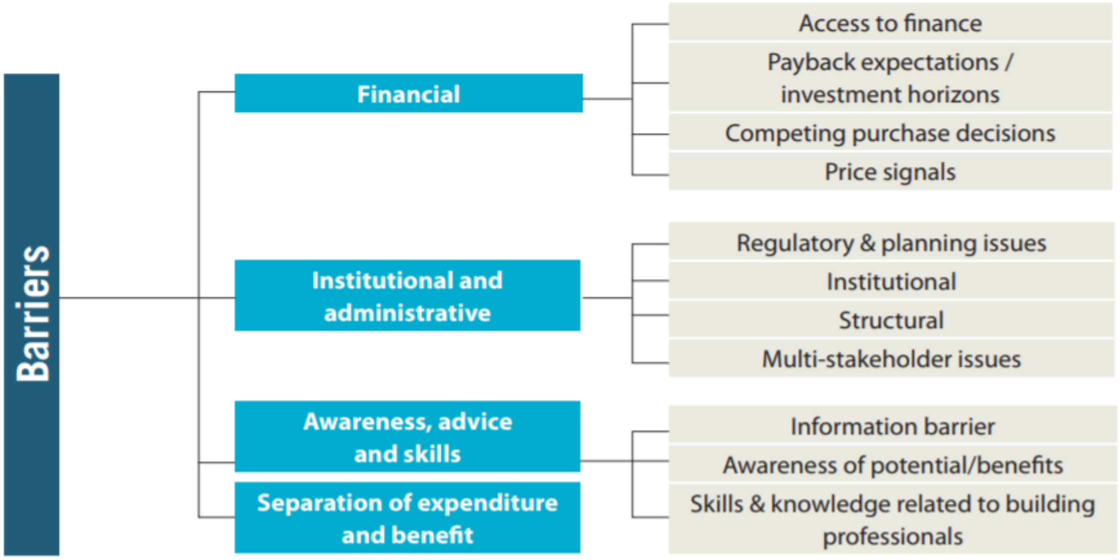


Figure 3: Classification of barriers to energy efficiency as identified by the BPIE survey (2011)

To improve the energy efficiency of buildings, the use of zero energy buildings (ZEB) has increased in recent years, buildings targeting zero energy goals have increased by 866% between 2012 and 2019, as shown in Figure 4 (NBI, 2019). The New Building Institute (NBI) has been verifying energy data for buildings that have stated zero energy goals since 2008. Their latest published report showed that a total of 580 projects attempted to reach zero energy, whether it was a new or a retrofitted project (NBI, 2019). Figure 5 shows the number and location of these projects throughout the U.S.

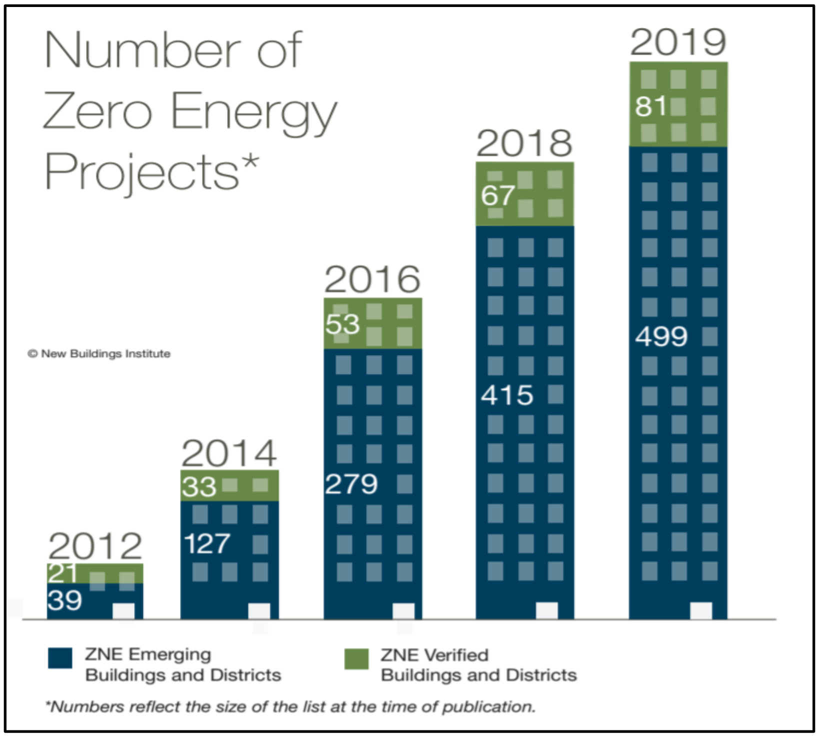


Figure 4: Number of verified and emerging zero energy buildings from 2012-2019 (NBI, 2019)

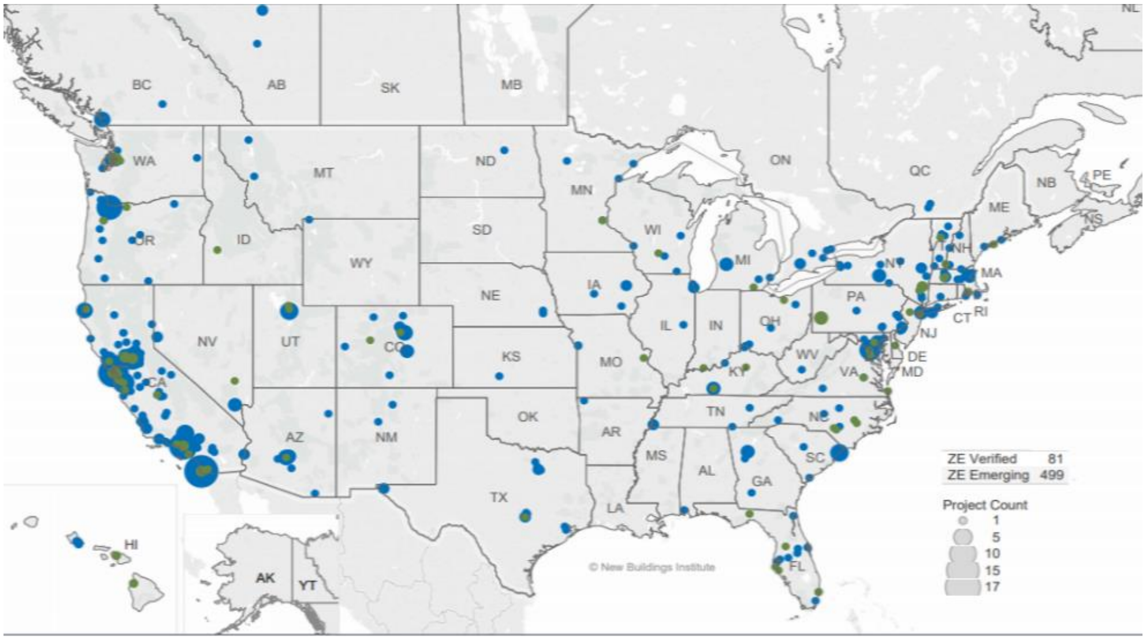


Figure 5: ZEB verified, and emerging projects plotted by city. (NBI, 2019)

A zero energy building (ZEB) produces enough renewable energy to meet its own annual energy consumption, thereby reducing the use of non-renewable energy. The Department of Energy defines the zero energy building as “an energy-efficient building where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy” (DOE, 2015). Reducing building energy consumption in new building construction or retrofit can be achieved by several methods, including integrated design, retrofits for energy efficiency, decreased plug costs, and energy conservation programs. Reducing the energy consumption of the building makes meeting the energy usage requirements of the building with renewable energy sources easier and less costly. Researchers suggest that ZEBs can be achieved by using three different approaches: passive approaches, energy-efficient methods, and renewable energy techniques (Belussi et al., 2019). Passive approaches include building orientation and shading, energy efficient measures include building envelope system, building services, and internal conditions, and renewable energy techniques include solar photovoltaic, solar thermal energy, and wind turbines. Figure 6 illustrates the fundamental steps followed by early adopters to achieve a ZEB using the abovementioned 3 approaches.

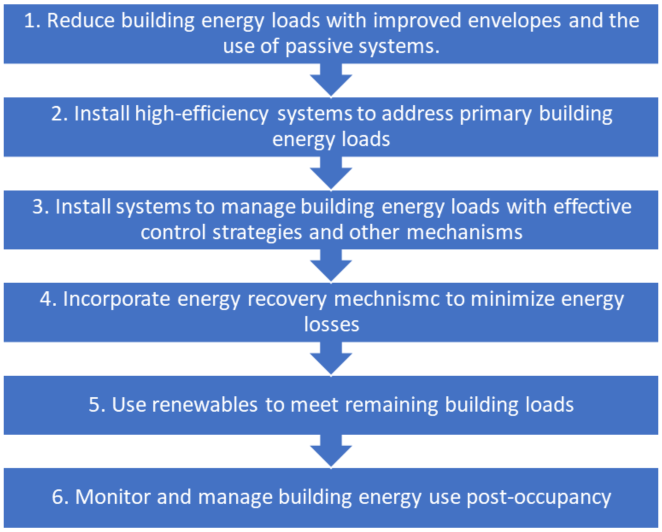


Figure 6: Steps to achieve zero energy building (PG&E, 2012) (Cortese and Higgins 2014)

1.2 Problem Statement

In spite of the recent increase in the construction of zero energy buildings, the majority of buildings were not able to meet the initial energy goal as shown in Figure 4, only 14% of the buildings targeting zero energy were able to verify that they met their goals over the course of at least 12 months (NBI, 2019). Several research studies have been conducted to investigate the different challenges and cause that confronts buildings targeting ZEB during design (Fanney & Healy, 2014), (Rahill, 2014), construction and operation (Brostrom, Director, Howell, & Eng, 2008), (Attia et al., 2017). Despite the contributions of the aforementioned studies, there is a lack of reported research that investigated and analyzed the challenges confronting the design and construction of zero energy buildings in the U.S.

1.3 Research Objectives

The primary goal of this research study is to investigate and analyze the challenges confronting the design and construction of zero energy buildings in the U.S. To accomplish this goal, the objectives of this research study are to:

(1) conduct a comprehensive literature review of the current practices and latest research conducted on zero energy buildings;

(2) evaluate the performance of a large education building, that was planned to be the largest ZEB in the U.S., as a case study, to analyze the challenges confronting its design and construction; and

(3) investigate the causes that prevented the analyzed case study from accomplishing its zero-energy goal, develop recommendations to enhance its current performance; and identify lessons learned that could be used to improve the design and construction of future similar ZEB.

1.4 Research Methodology

This section outlines the proposed methodology for achieving the objectives of this research study.

1.4.1 Task 1: Conduct a Comprehensive Literature Review

This task will focus on conducting a comprehensive literature review to identify and investigate the latest research focusing on ZEB at the campus level. The literature review will include the latest research on (1) definitions and approaches of ZEB adopted internationally and, in the U.S., (2) energy efficient features adopted in ZEB, (3) onsite renewable energy techniques, and (4) successful case study in North America.

1.4.2 Task 2: Data Collection

Task 2.1: Conduct and analyze interviews with different project stakeholders including designer/engineer, builder, building operator and users to gather data on (1) motivation behind the project, (2) project initial goal, (3) stakeholder's awareness of project energy goals, (4) design challenges, (5) construction challenges, (6) move-in plan and occupants' preparations, (7) current operation performance, (8) occupant's initial needs and current building experience.

Task 2.2 Case study data collection

The purpose of this task is to collect data to investigate further the reasons why the analyzed building has not been a success in reaching the zero-energy goal – Data includes; (1) energy designed load – from the energy model, (2) energy consumption and energy bills (EUI and dollar value) to analyze the energy performance of the building with reference to the designed energy load, (3) commissioning and retro-commissioning reports and their effectiveness on the energy performance of the building and, (4) renewable energy technique performance.

1.4.3 Task 3: Data Analysis and recommendations

The objective of this task is to analyze the actual performance of the building by analyzing and comparing measured energy consumption with the designed energy loads. In addition, we will investigate the reasons behind the deficiency in performance by inspecting different energy efficient systems incorporated in the building. Accordingly, we can develop recommendations for energy performance improvement. Finally, we will study the challenges that were involved in this project at different phases; design, construction, or operation and develop a list of lessons learned for future potential adopters.

1.5 Research Significance

This case study leads to significant contributions in a number of areas. First, a comprehensive literature review is presented to cover all the definitions, energy efficient measures, renewable energy techniques associated with ZEB, and challenges of early adopters of ZEB whether during the design, construction or operation. Second, documenting and studying a case study of one of the largest emerging ZEB projects, ECE building, to highlight sources of deficiency and to make recommendations to enhance the current energy performance of the Finally, we will present the lessons learned and make future recommendations for ZEB as a reference for future adopters.

1.6 Report Organization

The organization of this report and its relationship with research objectives, tasks, and deliverables are detailed in five chapters. Chapter 2 presents a comprehensive literature review that establishes baseline knowledge of the latest research in (1) definitions and approaches of ZEB adopted internationally and, in the U.S., (2) design approaches for ZEB, (3) onsite renewable energy techniques, and (4) a successful case study in North America. Chapter 3 covers a case study of an education building which includes: (1) building overview, (2) the main energy efficient features, (3) building design model (4) building energy consumption, (5) analysis of energy model and its accuracy, and (6) onsite renewable energy sources. Chapter 4 presents (1) causes preventing the studies case study to achieve its zero energy goal, (2) reccomendations to improve current energy performance of the building, and (3) lessons learned to be used by future adopters of a similar building. Chapter 5 presents conclusions and recommended future work.

CHAPTER 2 - LITERATURE REVIEW

2.1 Introduction

A comprehensive literature review has been conducted to establish a firm foundation for the proposed study. The literature review focused on investigating and analyzing the relevant research studies and current practices in the construction and operation of zero energy buildings (ZEBs). This chapter summarizes and organizes the reviewed literature into three main sections: (1) ZEB classifications and approaches; (2) their main design elements; and (3) a successful case study of a large education ZEB in the U.S.

2.2 Classifications and Approaches

In order to verify achieving a ZEB, the main elements of ZEB have to be identified using clear and concise language along with precisely specifying metrics and measurement guidelines that address building-grid interaction, energy uses and types, how energy consumption shall be measured and how zero energy goal shall be attained. (Marszal & Heiselberg, 2011). The literature indicated that there are different ZEB definitions and different classifications and approaches. This section will review major ZEB approaches in order to emphasize the crucial topics before formulating a common ZEB definition. What does the word ‘zero’ refer to: is it the source energy, end energy, CO_2 emissions or energy costs and bills?

A general definition of ZEB is provided by DOE Building Technologies Program (P Torcellini, Pless, & Deru, 2006): *“A net-zero- energy building (ZEB) is a residential or commercial building with greatly reduced energy needs through **efficiency gains** such that the balance of energy needs can be supplied with **renewable** technologies.”*. The authors discussed the issue of the ambiguity of the word ‘zero’ in ZEB, which lacks a common definition, or even a common understanding (P Torcellini et al., 2006). Additionally, authors indicated ZEB definition is determined based on the project goals, investor intentions, climate change considerations, greenhouse gas (GHG) emissions or energy costs. Accordingly, Torcellini et *al*. identified four commonly used definitions:

(1) Net Zero **Site** Energy: Energy produced by a building covers at least its usage in a year, accounted for at site.

(2) Net Zero **Source** Energy: Energy produced by a building covers at least its usage in a year, accounted for at the source. Source energy is the energy used to generate and deliver energy to the site. Total source energy = Imported + Exported energy X appropriate site-to-source conversion multipliers.

(3) Net Zero Energy **Costs**: the total cost in the utility bill should be at least equal to the value of energy exported back by the building to the grid over a year.

(4) Net Zero Energy **Emissions**: The emissions-free renewable energy produced from a building is at least equal to emissions-producing energy.

Analyzing these definitions and looking into their pros and cons, it can be inferred that the definition of “Site ZEB” does not consider all utility costs neither does it account for the types of energy used. Incorporating this element is very important when other types of energy sources are used besides electricity such as natural gas, propane, or other fuel. (P Torcellini et al., 2006). This concept was illustrated by an example (Bailes, 2013) “Let us say your home has a natural gas furnace, and it is 95% efficient. For every 95 kWh of heat that your home needs, your furnace is burning 100 kWh of natural gas. That means you have got to provide 100 kWh of site-generated electricity. If, on the other hand, you had a heat pump, it would need maybe 40 kWh of electricity to move 95 kWh of heat into your home. Rather than having to produce 100 kWh of electricity, then, you would only need to produce 40”. Moreover, thus, this definition favors on-site electricity use. Also, it is the simplest of all four definitions and is easier to implement and could be verified using site measurements.

As for “Source ZEB,” this definition accounts for the source energy. For a building that runs only on electricity, the source and site definitions are the same. It does not consider all utility costs as well; calculations are too broad for source Energy. Also, the development of the site to source conversion factor needs much information to be defined, which could be a challenge.

As for “cost ZEB,” it is easy to implement and measure ZEB according to this definition. A building that is “cost ZEB” is a building that earns as much money from selling electricity produced as it pays for electricity used. This could be easily verified from bills. However, the problem with this definition is that utility rates can vary, so a building with consistent energy performance could meet ZEB goal one year and not another (Bailes, 2013).

Finally, “Emissions ZEB” is a better model for green energy and makes ZEB an easier goal. However, appropriate emission factors are necessary and needed.

This classification of ZEB definitions was used in the literature in various publications including: “The Potential Impact of Zero Energy Homes”(The National Association of Home Builders Research Center, 2006), (P Torcellini et al., 2006), “Centerline”, (2008), Noguchi, (2008), (Kilkis, 2007a).

Another perspective of ZEB definitions (Kilkis, 2007b), specifically in balancing the ‘zero’ in both quantity and quality of energy are both considered. One disadvantage of the ZEB definition is missing the importance of exergy in evaluating the influence of the building on the environment.

For example, when power is generated in a thermal power plant by the district, and the ZEB generates its electricity using a wind turbine, they have different environmental impacts and exergy (Kilkis, 2007b). Kilkis suggested another definition for ZEB and defined it as: “a building, which has a total annual sum of zero exergy transfer across the building-district boundary in a district energy system, during all-electric and any other transfer that is taking place in a certain period of time” (Kilkis, 2007b).

Around the same time, another group of researchers, Mertz, et *al.*, identified two definitions for ZEB: “a net-zero energy building or a net-zero CO_2 (CO2 neutral) building”. Mertz, et al. (2007) describe a net-zero energy home “that over the course of the year, generates the same amount of energy as it consumes. A net-zero energy home could generate energy through photovoltaic panels, a wind turbine, or a biogas generator. The net-zero energy home considers in this paper uses photovoltaic panels (PV) to offset electricity purchased from the grid.”. “In a CO_2 neutral home, no CO_2 is added to the atmosphere due to the operation of the building. This could be accomplished by purchasing tradable renewable certificates (TRC’s) generated by solar, wind, or biogas. It could also be accomplished by purchasing CO_2 credits on a carbon trading market form some who has CO_2 credits to sell. Also, the home could generate all of its energy on-site like a net-zero energy home” Mertz, et al. (2007).

2.2.1 Defining zero energy buildings in the U.S.

To create a broad, accepted, and agreed upon definition of ZEB, different parties that have an interest in the outcome of the project shall be involved in the process. In response to Section 914 of the Energy Policy Act in 2007, the NIBS’ High-Performance Building Council (HPBC) directed the process to develop commonly agreed-upon definitions for ZEBs. The HPBC had a representative from major standards writing organization, industry trade associations, NPO and federal government entities involved with the built environment. It also included different stakeholders involved in any ZEB project, including the Designer, Contractor, and End User. (DOE, 2015a)

2.2.2 Establishing a national ZEB definition - DOE

In 2014, the U.S. Department of Energy (DOE) in cooperation with the National Institute of Building Sciences (NIBS) made an effort to set up definitions, pertinent terminologies, and measurement guidelines for ZEB. The purpose of this initiative was attempting to achieve consistent implementation and practice of ZEB by the construction industry (DOE, 2015a). NIBS is a non-profit, non-governmental organization. The U.S. Congress founded it in 1974. The primary mission of NIBS was to gather representatives from the government, the industry, and the end-users as well as regulatory agencies to focus on identifying and resolving problems that may come in the way constructing affordable and efficient structures in the United States.

The output of this research project underwent many revisions by experts and different stakeholders. DOE announced the reviewed material in the Federal Register, Docket EERE-2014-BT-BLDG-0050 Definition for Zero Energy Buildings. (DOE, 2015a)

2.2.3 Terminology and definition: nZEB = ZEB = NZE = ZNE

NIBS had an issue that was addressed during the revision process of the research outputs with different stakeholders, and that is “what to call buildings that are designed and operated in such a way that energy consumption is reduced to a level that it is balanced by renewable energy production over a typical one-year period?”. Researchers collected opinions of experts and different stakeholders to determine the terminology that would concisely describe the above statement while also reflecting DOE programs and goals. The DOE Zero Energy Ready Homes Program brought an essential factor in reaching a conclusion that the term “net” was sometimes confusing to consumers. Although some opinions were with adding the word “net” to the term Zero Energy Building as it reflected the consideration of energy usage, eventually the research team reached the conclusion that it did not add any significant meaning to the term since the definition fully accounted for energy sources and usage. Thus, in striving for simplicity, consistency, DOE, and NIBS selected the term *“Zero Energy Building (ZEB)*.” And defined it as

“Zero Energy Building (ZEB): *An energy-efficient building where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy.”*(DOE, 2015a)

However, other terminologies such as *Net Zero Energy (NZE)* and *Zero Net Energy (ZNE)* were also recognized as they are in wide use and convey the same meaning as Zero Energy Building.(UGBC, 2017)

2.2.4 NIBS-DOE: ZEB definition variations

During the review process, the research team recognized the necessity for supplementary definitions for related building groupings. According to the NIBS report named “A common definition for ZEB” submitted to the DOE in 2015 the definition shall (1) create a consistent identification of ZEBs especially for industry, (2) be measurable and testable and should be rigorous and transparent, (3) guide the design and operation of the building to significantly decrease the building’s energy consumption, (4) be clear and understandable by industry and policymakers, (5) set a long-term goal and be durable for some time into the future.

2.2.5 ZEB site boundary

In order to understand energy performance for a ZEB, it is essential to clearly set the “boundaries” of energy usage or production included in any definition. In recent years, national and international standards have produced diagrams to illustrate how to account for energy consumption in a building or site. Many boundary diagrams produced over the years before 2015 were considered during the development of the U.S. Department of Energy (DOE) Common Definition for Zero Energy Buildings (DOE, 2015a). This common definition is one of the more comprehensive definitions found in the literature. DOE aimed to simplify ZEB concepts to make them more easily recognized and understood by both experts and technical audience from the industry, as well as the general public. The “site boundary” diagram included as part of the U.S. DOE ZEB definition is shown below in Figure 7.

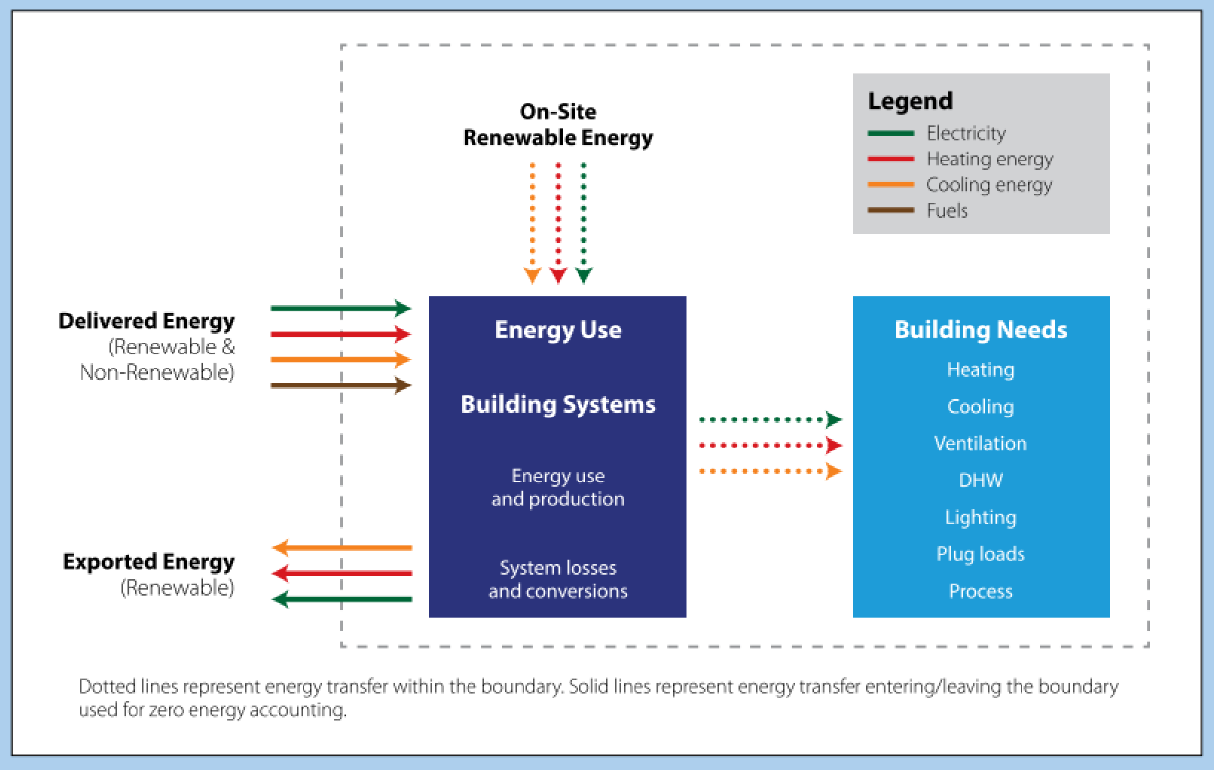


Figure 7: Site boundary of energy transfer for zero energy accounting (DOE, 2015)

2.2.6 Overview of international ZEB definitions and parameters

European Union: *Nearly Zero Energy Building (nearly ZEB): "A building that "has a very high energy performance with the nearly zero or very low amount of energy required covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby."* (EPBD 2010/31/EU, 2010)

In Japan, *to support government ZEB policies, the Society of Heating, Air-Conditioning and Sanitary Engineers of Japan (SHASE) defined ZEB as "…a building that has high energy saving through load reduction, natural energy use, and efficient appliances without decreasing the environmental quality both indoors and outdoors. With the introduction of on-site renewable energies, the on-site energy generated will be equal to or greater than the actual energy consumed within the building in the course of a year."* (SASHE, 2015)

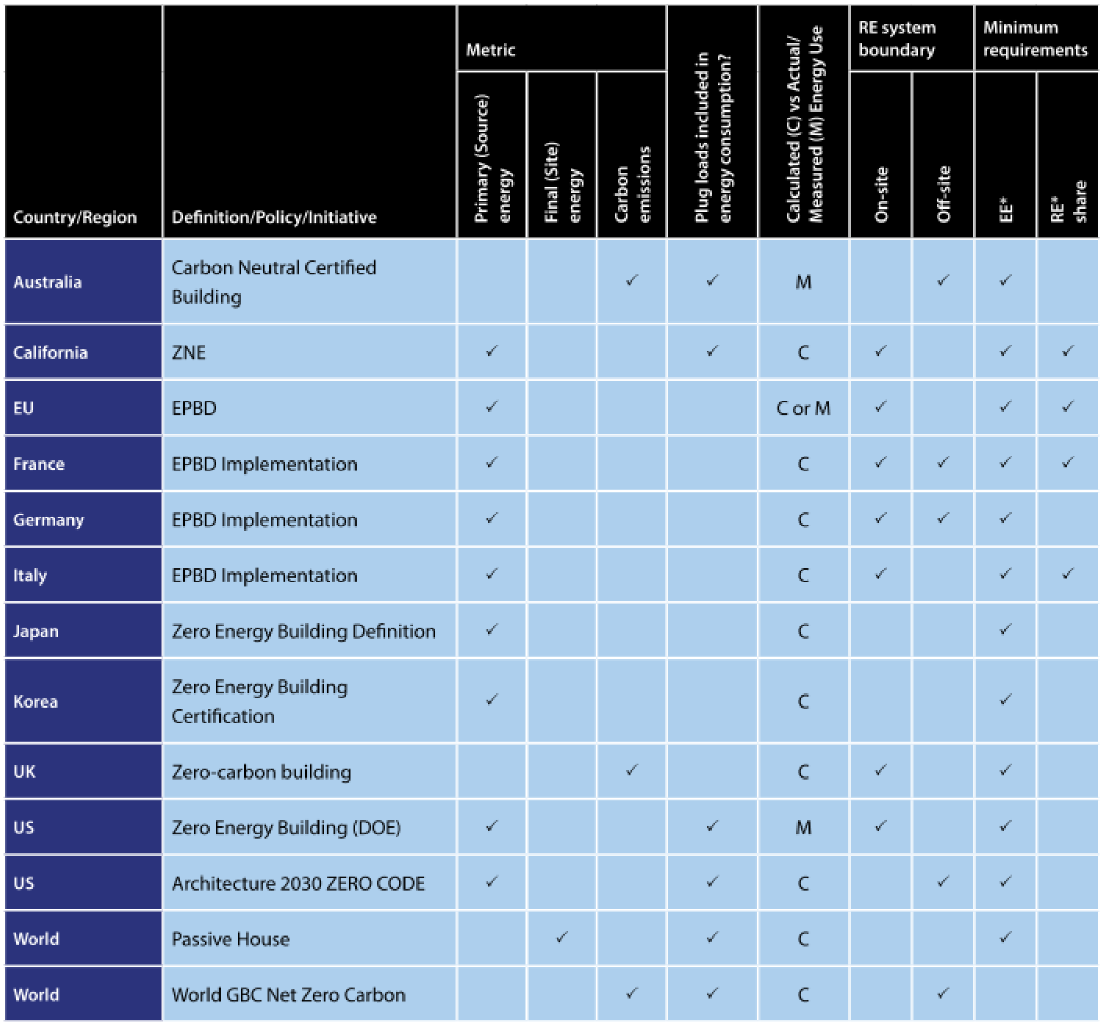
The World Green Building Council (WGBC*) has defined a net-zero carbon building as "A highly energy-efficient building with all remaining operational energy use from renewable energy, preferably produced on-site but also off-site production, to achieve net-zero carbon emissions annually in operation."* (UGBC, 2017).

Table 1 below compiles a summary of different requirements in some of the international ZEB parameters, including the determined metrics, boundaries, and specified minimum requirements.

Below is a summary of the conclusions of the range of definitions:

- The primary energy source is the most common metric considered.
- The base level of energy efficiency is a typical prerequisite and is often an essential parameter of the definition.
- European definitions from Europe most likely include a minimum requirement for renewable energy (RE). This is probably due to the European Union Energy Performance of Buildings Directive EU EPBD Directive which is otherwise not common outside of Europe.
- Plug loads are left out in most European definitions and seldom left out in U.S. definitions.
- These definitions are mainly applied to new construction projects, and thus, it uses calculated energy performance except for U.S. DOE uses actual/measure performance.

Table 1: Key parameters and boundaries in leading ZEB definitions (IPEEC, 2018)



Country/Region	Definition/Policy/Initiative	Metric			Plug loads included in energy consumption?	Calculated (C) vs Actual/ Measured (M) Energy Use	RE system boundary		Minimum requirements	
		Primary (Source) energy	Final (Site) energy	Carbon emissions			On-site	Off-site	EE*	RE* share
Australia	Carbon Neutral Certified Building			✓	✓	M		✓	✓	
California	ZNE	✓			✓	C	✓		✓	✓
EU	EPBD	✓				C or M	✓		✓	✓
France	EPBD Implementation	✓				C	✓	✓	✓	✓
Germany	EPBD Implementation	✓				C	✓	✓	✓	
Italy	EPBD Implementation	✓				C	✓		✓	✓
Japan	Zero Energy Building Definition	✓				C			✓	
Korea	Zero Energy Building Certification	✓				C			✓	
UK	Zero-carbon building			✓		C	✓		✓	
US	Zero Energy Building (DOE)	✓			✓	M	✓		✓	
US	Architecture 2030 ZERO CODE	✓			✓	C		✓	✓	
World	Passive House		✓		✓	C			✓	
World	World GBC Net Zero Carbon			✓	✓	C		✓		

Regardless of the attempts of prominent organizations and policymakers to determine a common definition of zero energy buildings, different standards sometimes differ in their definitions of some terminologies associated with ZEB. For example, the definition of “regulated energy” varies from a standard to another. Also, what are the final usage of energy that will be considered in calculating energy consumption? Example of those could be found in the blue box in Figure 7.

2.3 Design Approaches

The basic elements of definitions discussed above are summed up in Figure 8.

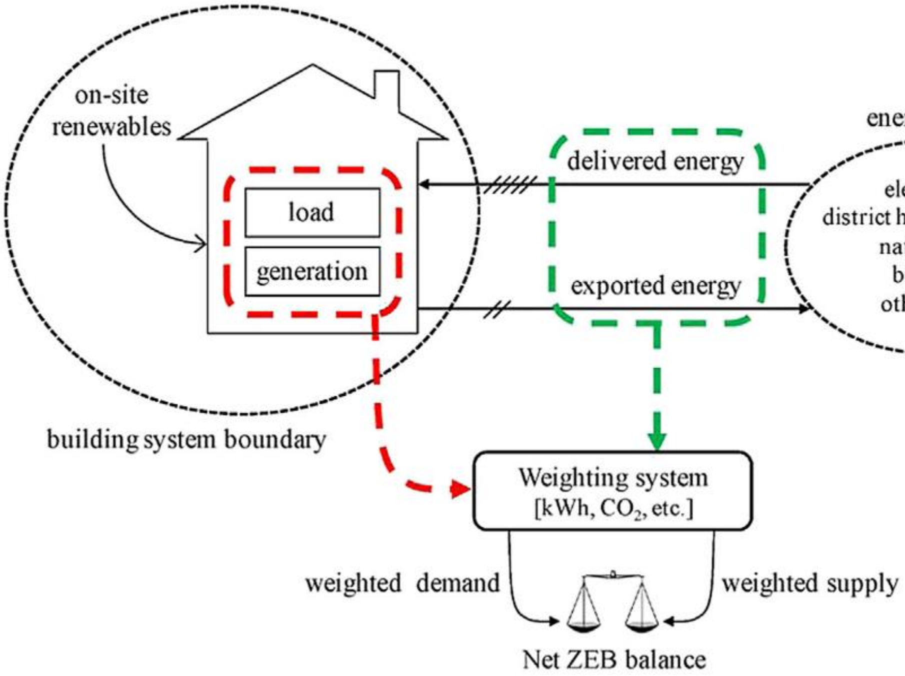


Figure 8: System Structure and basic elements of ZEB, (Paul Torcellini et al., 2010)

ZEB mainly considers three kinds of energy efficiency measures: passive design, active system and power generation from Renewable Energy Source (RES) as shown in Figure 9(Paul Torcellini et al., 2010).

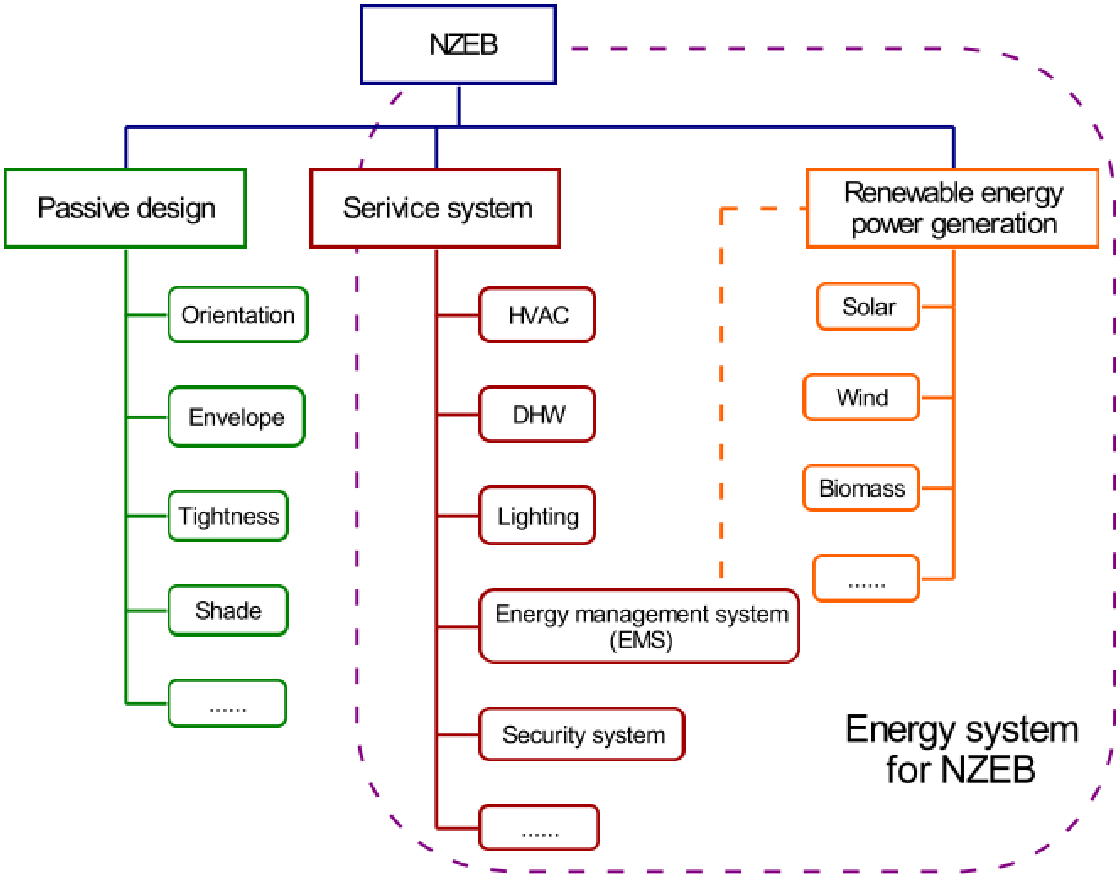


Figure 9: Design elements for NZEB, (Paul Torcellini et al., 2010)

An excellent passive design for the building, which may also consist of optimized orientation, high-performance thermal-isolation envelope, proper tightness, and properly-designed shade for windows, decreases typically the thermal and electrical load of buildings. In order to meet the reduced loads, numerous HVAC (heating, ventilation, air-conditioning) systems, DHW (domestic hot water) systems, lighting systems, etc., are proposed. The practical purpose of such systems is to create a comfortable and indoor environment for occupants residing efficaciously. Necessarily, various energy sources, including natural gas or electric energy, are needed to drive building service systems (BSS). For this reason, the renewable energy power (REP) system has to be installed to offset energy intake. In this way, a ZEB could be feasible with electricity and thermal production from the renewable power source, if enough energy capacity could be installed. The phrase of “BES (building energy system)” normally refers back to the combination of BSS and REP system, because increasingly more ZEBs choose to use some integrated systems, which includes bio-gasoline CCHP (blended cooling, heating, and power), photovoltaic thermal collector, and so forth. The renewables are utilized not only for the energy generation but also for the heating, cooling, or DHW system, as a 100% renewable energy solution for sustainable buildings (H. Lund, 2010). Therefore, a clear distinction between BSS and REP system is maybe disappearing due to greater integration forms of RES in ZEB. New configuration or integration will make BES more compact and reliable to ZEB.

2.3.1 Passive approach

This section contains a comprehensive review of passive design approaches to minimize energy usage in a building targeting zero energy.

Building form, site, and orientation

The geometry of the building plays a vital role in energy demands. Hence, designers need to avoid any irregular shapes in the building design that might result in energy consumption. Multiple shapes such as dormers, bay windows, long narrow extensions, and split level increase the energy cost associated with a building. It is preferred to have a compact building with less surface area that allows heat losses. This will influence the heating and cooling demand, independent of the U-value of the building fabric. Additionally, the energy consumption of a building is affected by their orientation. The distance between buildings is a crucial factor in the amount of daylight each building receives, so buildings should not shade each other.

Airtightness

Good airtightness to avoid air leakages results in reduced heating and cooling consumption. Air leakage may occur when cracks exist in the building fabric, or due to the presence of poorly sealed windows and doors. ZEBs need a minimum value for airtightness. It is defined by the number of air changes in the building per hour at a specific pressure difference between outdoors and indoors.

Thermal insulation

Avoiding thermal losses is crucial to the success of any ZEB. For this reason, thermal transmittance coefficients have to meet the requirements of current building regulations. Regarding insulation materials, the most common ones include mineral wool, fiberglass, and cellulose. Polystyrene and polyurethane are used as ground insulation in ZEBs. Vacuum insulation is another technique to reduce losses.

Thermal bridges

A thermal bridge is formed when the heat flows perpendicular to the surface. Thermal bridges play a crucial role in terms of buildings energy efficiency. The goal is to minimize thermal bridging to increase energy efficiency. Thermal bridging can be eliminated through the insulation of sensitive junctions with low thermal conductivity materials.

2.3.2 Active approach

Lighting

Lighting has a vital function in any building. Sun provides light and heat every day. Daylight can save energy that can be used later for heating and electric lighting. Compact Fluorescent Lamps

(CFLs) and Light Emitting Diodes (LEDs) have high efficiency and are recommended to reduce energy consumption. One of the solutions for lighting is to use white paint to reduce energy consumption.

Renewable Energy Sources

Renewable energy utilized to offset energy consumption of a building should be onsite or in a nearby location. According to the definition of ZEB (DOE, 2015b), renewable energy cannot be offsite and therefore renewable energy sources such as hydro energy, which derives power by utilizing energy from falling water on an turbine or wheel and converts kinetic energy to mechanical energy then energy is converted to electrical through a generator, cannot be utilized to offset energy consumption for ZEB. The most common onsite renewable sources includes solar and wind energy (Pless & Torcellini, 2010).

2.4 Renewable Energy Sources

For zero energy buildings, renewable energy from solar by utilizing photovoltaic modules has been commonly used to offset energy consumption. Solar PV modules converts solar energy into electricity. The panels are installed on the building in locations that receives maximum daily sunlight, typically the roof (Pajarskas, 2017).

Another renewable energy source is wind energy. “Wind power is generated by using wind turbines to harness the kinetic energy of wind. Wind blowing across the rotors of a wind turbine causes them to spin. The spinning of rotors converts a portion of the kinetic energy of the wind into mechanical energy. A generator further converts this mechanical energy into electricity.(Hakkarainen, Tsupari, Hakkarainen, & Ikäheimo, 2015)” Figure 10 shows a typical wind energy system.

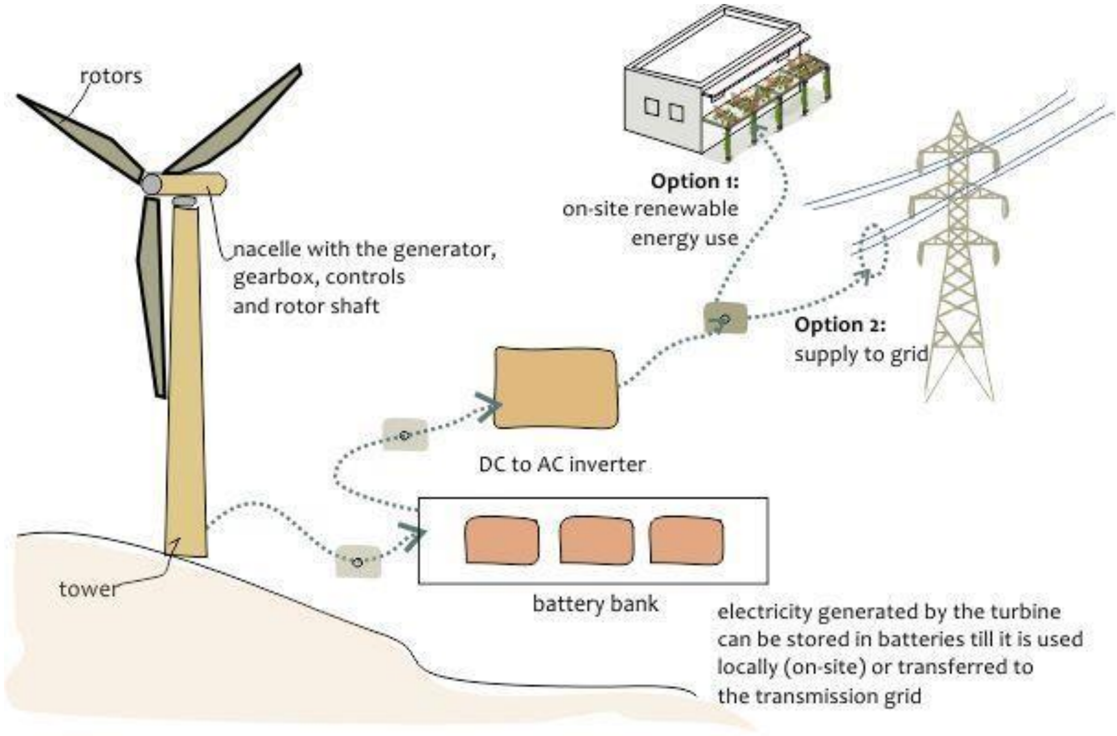


Figure 10: A typical wind energy system

2.5 Case Study

This section covers successful zero energy building case study from North America. The review is mainly focusing on a commercial building with a large area (>100,000 sf).

2.5.1 Department of Energy's National Renewable Energy Laboratory Research Support Facility (RSF)

Project summary

The RSF is an office and data center building with an area of 222,000 sf with a maximum capacity of 825 employees, located in Golden, Colorado. It is owned by the U.S. Department of Energy and the National Research Energy Laboratory (NREL). The delivery method of this project was a design-build method which consisted of a general contractor, architect, mechanical and electrical engineer, sustainability consultant, design build RFP consultant, and a design-build owner representative. The contract type was performance-based design with a firm fixed price of $80 million. The total design phase lasted 3 years, from 2006 to 2008. The construction phase lasted a year and half from early 2009 to mid-2010. The building operations commenced in June 2010. The energy goal was 35.1 kBtu/ft^2/year, including a data center. The building's energy performance was 50 % better than ASHRAE 90.1, 2004 Standard

The RSF implemented multiple high-performance design aspects, including both passive energy strategies, and renewable energy technologies. The building has a narrow floor plate (60' wide) that allows daylight and natural ventilation in all spaces. East and west glazing is minimized by selecting optimum building orientation and geometry. A labyrinth of massive concrete structures is found in the RSF crawl space. The primary function of the labyrinth is storing thermal energy and providing additional capacity for passive heating of the building.

100 % of the workstations are operated under daylight. Daylight enters through the upper windows and reflected into the whole space using light-reflecting devices. Occupants are allowed to open some windows to fill the space with fresh air and naturally cool the building. In addition, a thermally massive exterior wall assembly, using an insulated precast concrete panel system, is added to provide significant thermal mass to moderate the building's internal temperature.

Approximately 42 miles of Uponor tubing is used in the radiant piping that use water for cooling and heating in most of the workspaces — instead of forced air. In addition, underfloor ventilation is added where a demand-controlled outside air system delivers fresh air on the hottest and coldest days. Ventilation is distributed through an under-floor air distribution system.

A fully contained hot and cold aisle data center configuration allows for effective air-side economizer cooling with an evaporative boost when needed while capturing waste heat for use in the building. Plug loads are minimized with extensive use of laptops and high-efficiency office equipment. Regarding renewable energy sources, approximately 1.6 MW of on-site photovoltaics (PV) are installed and dedicated to the RSF. In addition, Power Purchase Agreement will add PV power, and another PV sources in the adjacent parking areas is purchased with 2009 American Recovery and Reinvestment Act funding. In addition, a solar collector, developed by NREL, is used to preheat the outside ventilation air.

Finally, the engagement of employees, occupants of the RSF, was critical to the success of the project. Employees have to understand and share the same ideas about saving energy. In addition, the workplace culture and employees actions during a workday were changed to meet the energy efficiency requirements. For example, it is not allowed to use tall interior partitions that can block daylight, and the whole building's lights and equipment are turned off at night.

2.6 Summary

In this chapter, a review of ZEB classifications and approaches was presented. Multiple definitions of ZEB are based on on-site energy, source energy, energy cost, or emissions. The passive approach includes building form, airtightness, thermal insulation, and thermal bridges. The active approach includes lighting, ventilation, heating systems, and renewable energy technologies. Major design elements required to achieve ZEB were detailed. The literature review focused on investigating and analyzing a relevant research study and showed practices to achieve the goal of zero energy buildings (ZEBs).

CHAPTER 3 - CASE STUDY OF ZERO ENERGY BUILDING

3.1 Introduction

The objective of this chapter is to present a case study of the Electrical and Computer Engineering (ECE) building that was designed to be the largest zero energy education building in the U.S. Despite this planned design goal of the building, it has been unable to achieve zero energy performance. This chapter presents (1) a building overview; (2) building energy efficient features; (3) building energy model; (4) measured building energy consumption; (4) accuracy of building energy model; and (5) building renewable energy sources.

3.2 Building Overview

The new Electrical and Computer Engineering (ECE) building at the University of Illinois Urbana-Champaign is a 238,000 square foot (sf), five-story teaching and research building. The ECE building is located on the north engineering quadrangle of the campus in the city of Urbana, Illinois, as shown in Figure 11. The ECE building has 18 classrooms, 21 instructional labs, 19 meeting rooms, shared spaces, a coffee shop, a 5,000 sf cleanroom, 400-seat auditorium, and 48 private offices. The building users have 24-hour, 7 days a week access to the facility. The project was completed in 2014 and started full operation in September 2015. The total project cost was $95 million, which was funded half by the State of Illinois and half by private and corporate donations (Moone, 2011).

Figure 11: Top view shot of the site from Google Earth

The facility is owned by the Department of Electrical and Computer Engineering, University of Illinois – Urbana-Champaign. The architectural and structural designs were completed by Smithgroup, and the mechanical and electrical designs were completed by KJWW Engineering Consultants (currently known as IMEG Corporation). The main contractor for this project was Williams Brothers Construction. A view of the ECE building from different directions is shown in Figure 12 and Figure 13.

Figure 12: West Elevation of ECE, courtesy of Smithgroup

Figure 13: Image of the northeast side of the ECE, courtesy of Smithgroup

The ECE building serves as the department’s center of multidisciplinary research and education. From its early inception, it was intended to be the largest education building to achieve zero energy performance in the U.S. The ECE building was envisioned to serve as a blueprint for the future of ZEB and to influence others in the construction industry to pursue ultra-energy efficiency and net zero energy performance. In addition to targeting zero energy, the ECE building is also currently seeking certification for LEED platinum 2009.

It was crucial to unify zero energy objectives for the project team by clearly outlining the adopted ZEB definition. According to Professor Phillip Krein, the chair of the ECE building committee, the consensus on this project was to account for the energy use by only considering what the meters recorded as energy input to the building. The efficiencies of the campus central plant were not considered in the calculations during the design phase, thereby adopting the definition of zero site energy (DOE, 2015b).

The ECE building is served by the campus central chilled water and steam plants. Chilled water is provided to meet the majority of the building's cooling load. Chilled water is supplied to the onsite chilled beams, cooling coils in central air handlers, fan-coil units, and blower-coil units. The condensed steam is distributed to finned-tube radiation units located at exterior walls, heating coils in central air handlers, fan-coil units, blower coil units, cabinet, and suspended unit heaters.

3.3 Energy Efficient Building Features

An engineering building such as the ECE building, by nature, consumes a significant amount of energy since students have access to the building 24 hour a day, 7 days a week. Also, mechanical systems and research equipment have to run at all times, which increases energy consumption. For example, exhaust fans in the cleanroom are operating at all times to purify the air and maintain particles below a specific level. In order to advance its design goal of achieving zero energy performance, multiple energy-efficient features were incorporated in the ECE building to minimize its energy consumption, as shown in Figure 14. These features can be grouped into two categories: passive and active design approaches. These two groups of energy efficient features will be discussed in the following sections.

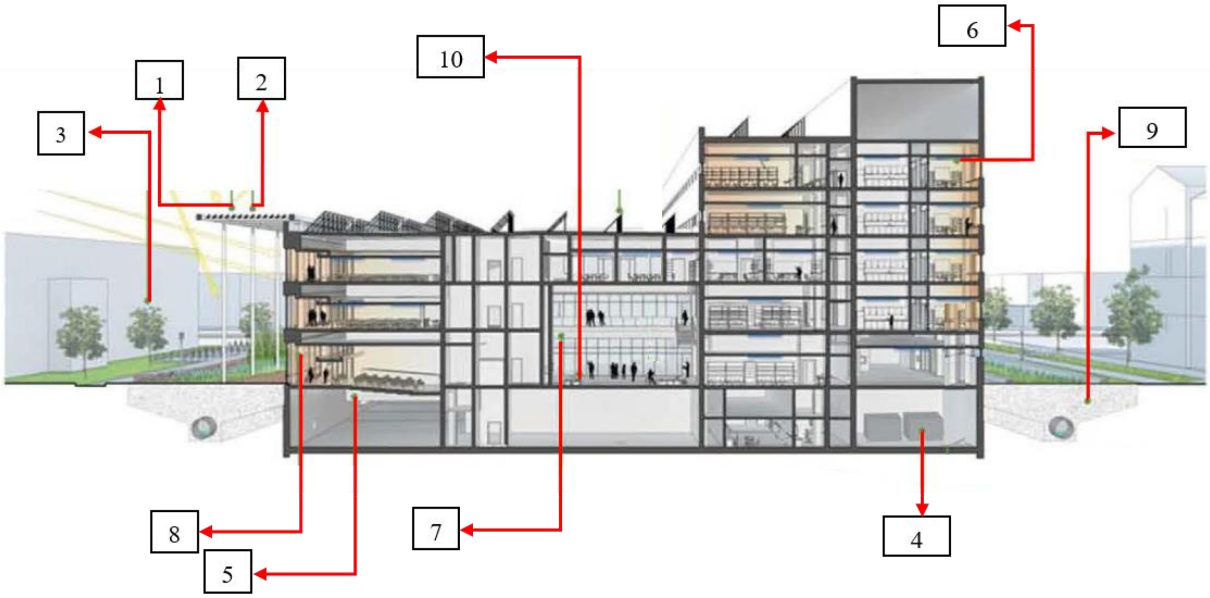


Figure 14: Main energy efficient and sustainable features: 1) enhanced building envelope, 2) passive solar, 3) heat recovery chillers, 4) displacement ventilation, 5) chilled beams, 6) lighting, 7) occupancy sensors and control, 8) native landscaping, 9) recycling, and 10)water efficiency

3.3.1 Passive design features

Passive design features are building components that are parts of the building or permanently attached to it. The passive design features included in the ECE building includes (1) enhanced building envelope, and (2) passive solar.

1. **Enhanced building envelope:** This passive design feature focused on enhancing building envelope and optimizing orientation to benefit from the daylight but also protect the building from the heat. The building envelope included solar screens and a three-story solar canopy of angled louvers, as shown in Figure 15. The exterior wall construction consists of terracotta clay cladding panels in a rainscreen assembly that includes an extruded aluminum subframe which covered 70% of the building envelope with an overall thermal value of R30. In addition,

approximately 80% of the windows are either shaded by the south solar canopy or by the terracotta panels. The albedo white roof consists of a white thermoplastic polyolefin with an overall thermal value of R30. These energy efficient features maximized energy savings without sacrificing occupant's comfort by allowing daylight into the building, maintaining views to the outside and most importantly protecting the building from the solar heat gain, especially during summer.

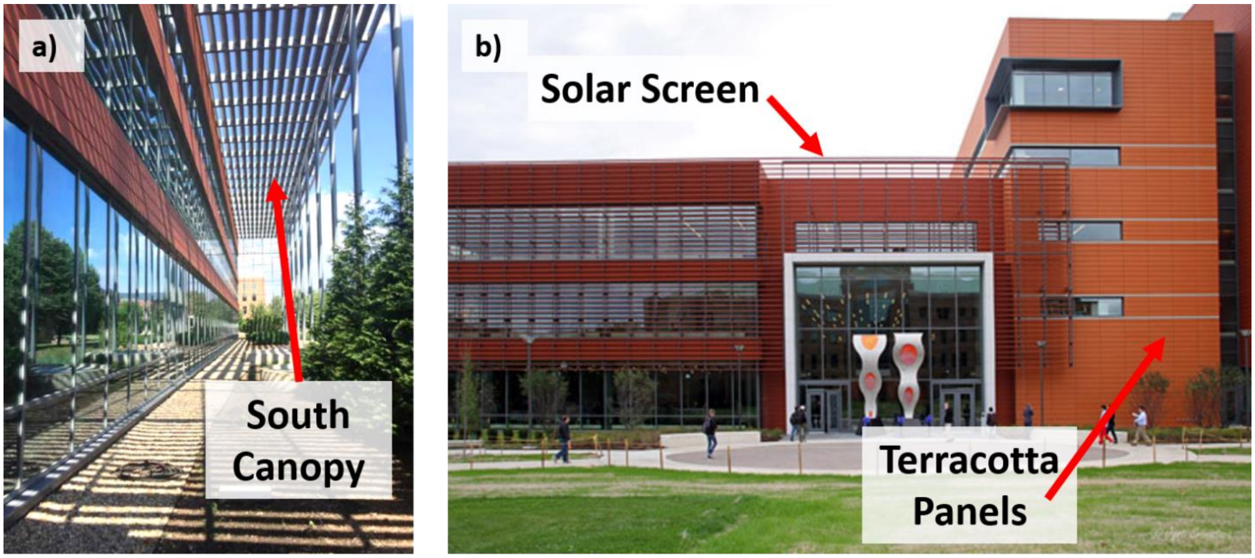


Figure 15: ECE building envelope a) South canopy, b) Terracotta panels and solar screens on the east side

2. **Passive solar:** This energy efficient design feature was accomplished by ensuring that the building orientation locates the majority of its glazing facing south for optimal daylighting and reduced energy loads.

3.3.2 Active design features

Active design features are building component that actively operate, interact with other building components, and their efficiency can affect the overall building performance. The active energy efficient measures that were incorporated in the ECE building included 13 Air handling units (AHU) that utilize systems such as heat recovery systems, chilled beams, and displaced ventilation to meet the heating and cooling loads of the building efficiently.

3. **Heat recovery chillers:** The heat recovery system preconditions and dehumidifies outdoor air before pumping it into the building and recovers energy from the return air to save energy before exhausting the air outside the building, as shown in Figure 16a. During winter, the indoor air passes through the heat wheel and heats that portion of the wheel. When the heated portion of the wheel rotates into the outdoor air stream, it pre-heats the incoming outdoor air. This heat transfer process reverses as cooling and heating need changes. The heat recovery system also produces hot water for the building using two onsite heat recovery chillers (HRC). HRC uses condensed steam to heat and reheat throughout the building while simultaneously producing chilled water as a useable byproduct. Any excess chilled water produced will be fed back into the campus chilled water network to be stored or used by other buildings.

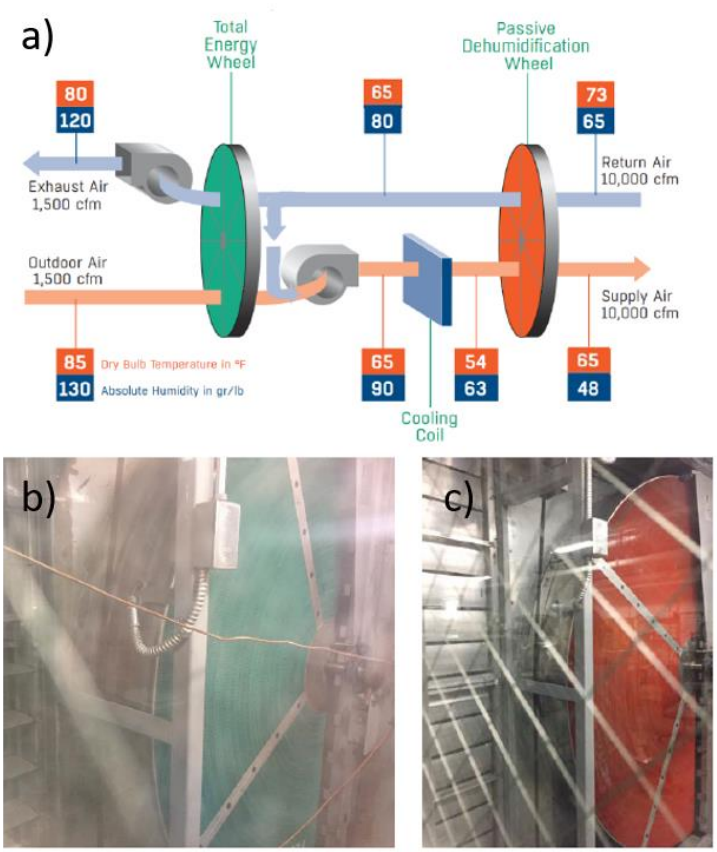
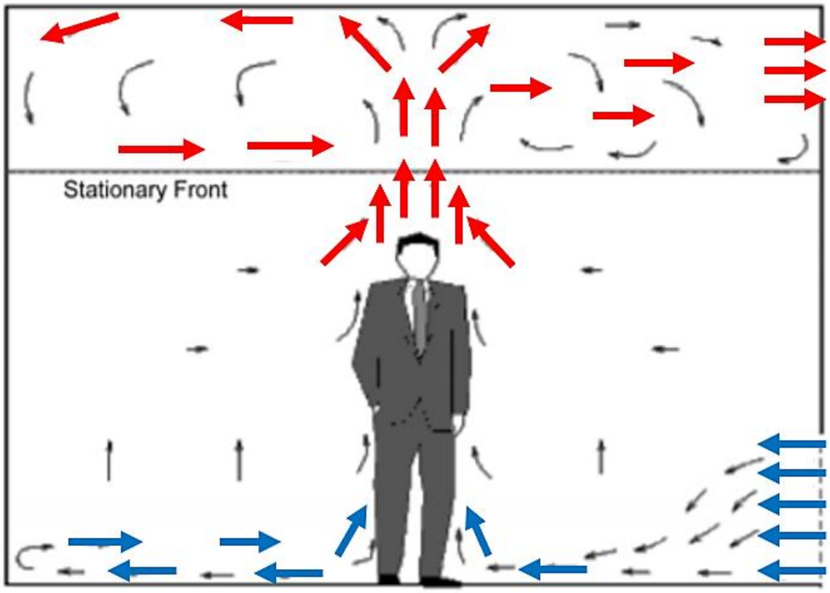


Figure 16: a) schematic of the dual wheel air handler unit, b) image of total energy wheel and c) image of passive dehumidification wheel.

The aforementioned heat recovery system in the building offers several benefits including energy saving, enhanced indoor air quality, and fresh air ventilation. These benefits are provided by the heat recovery system that complies with three different standards: (1) ASHRAE 90.1, energy standard for buildings except low-rise residential buildings, (2) ASHRAE 62.1, ventilation for acceptable indoor air quality, and (3) ASHRAE 55, thermal environmental conditions for human occupancy.

4. Displacement ventilation

Six AHUs also provide ventilation air and cooling through the chilled beam system to offices, labs, classrooms, and corridors throughout the building. The largest air handler unit, AHU-4, provides ventilation through a displacement ventilation (DV) system on the first-floor auditorium. Displacement ventilation system, shown in Figure 17, provides cool fresh supply air directly to occupants in different locations. The fresh air is pumped at a low velocity near the floor and spreads in the room to get into contact with heat sources. The supplied air slowly rises as it heats up, sucking heat around occupants and equipment. The warm air rises until it gets exhausted from the space at the ceiling (Energy Design Resources, 2014).



Source: Architectural Energy Corporation

Figure 17: Displacement ventilation system Architectural Energy Corporation

5. **Chilled beams:** The chilled beam system (Figure 18) provides cooling through natural convection and radiative heat transfer. Primary air is discharged into the space through the nozzles, while a larger volume of room air is induced across the heat exchanger coil which has chilled water circulating. The chilled beam system saves energy by utilizing the heat transfer properties of water, which makes the cooling process possible by circulating small amounts of chilled water. In addition to the energy savings realized by the chilled beam system, it uses less ceiling space compared to conventional cooling systems, lower construction costs, and requires minimal maintenance.

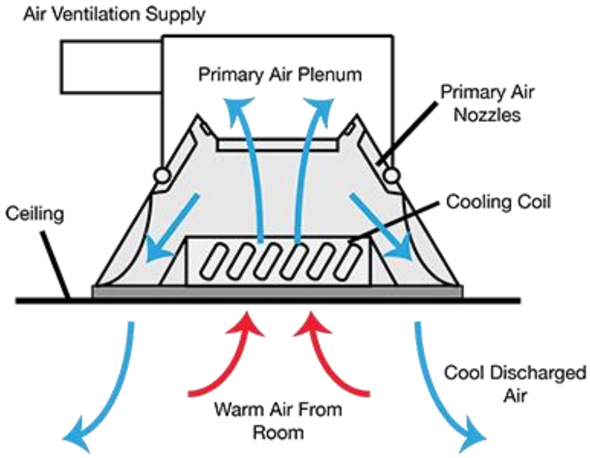


Figure 18: Chilled beam system

6. **Lighting:** The lighting used in the ECE building is provided by a mixture of a light emitting diode (LED) and 32-Watt T8 fluorescent fixtures. Lighting is locally controlled through wall switches and occupancy sensors to minimize usage while spaces are unoccupied.

7. **Occupancy sensors and control:** A lighting control system is used to control the lighting based on the time of the day and inputs from the occupancy sensors. For example, a dimming

daylight harvesting control scheme is used in all exterior zones to take advantage of natural daylight to reduce overall energy consumption. Also, carbon dioxide (CO_2) sensors are installed in the main lecture halls and classrooms to detect CO_2 levels and automatically control the operation of the ventilation system such that when the sensor's readings show high concentration of CO_2 it automatically turns on the ventilating system to enhance the indoor air quality and increase occupants' comfort.

8. **Native landscaping:** This design feature selected plant types that are primarily self-sustained and native to eliminate the need for an irrigation system and ensure seamless integration with the local habitat.

9. **Water efficiency:** Permeable pavers and an infiltration trench were used to promote infiltration of stormwater and reduce discharge from the site. In addition, low-flow and motion censored fixtures were used inside the building.

10. **Recycling:** Recycled and regional building materials were used in addition to recycling centers distributed throughout the building.

3.4 Building Design Model

The energy design and modeling of this building was performed using Trane™ TRACE® 700 (version 6.3.1) by KJWW Engineering Consultants. TRACE is a software package that allows hourly simulation of different energy uses in commercial buildings throughout the course of one year. The weather data used in this modeling represented a typical meteorological year for Springfield, Illinois that closely resembles the weather conditions in Urbana, Illinois. The accuracy of the model depends on the designer's choice of the software and its modeling abilities, precision of input loads and system controls, variations in actual weather patterns, and correctness of predicted building usage. The developed energy building model for the ECE building was based in a total area 199,455 net square foot (nsf). Two models of the same building to illustrate the savings realized by implementing the abovementioned energy efficient features into the ECE building rather than only implementing the minimum energy code requirements. The first model was the baseline building and was modeled according to ASHRAE 90.1-2007 baseline requirements. The second model was the proposed building and was modeled according to the building construction documents that included the aforementioned energy efficient features.

3.5 Measured Building Energy Consumption

This section presents an analysis of the ECE building measured energy consumption that was calculated based on the data collected from the four main meters installed in the ECE building: (1) 0409-E1, (2) 0409-E2, (3) 0409-CS1, and (4) 0409-CHW1. The first and second meters record electricity consumption, while the third and fourth record steam and chilled water consumption, respectively. This study will analyze the measured energy performance of the ECE building over a period of 48 months, from fiscal year (FY) 2016 to FY 2019.

3.5.1 Electricity consumption

The measured monthly electricity consumption of the ECE building over the last four fiscal years illustrates that peak electric usage occurs in winter between November and January, then usage gradually drops as the weather temperature increases, as shown in Figure 19 . The energy TRACE model showed that consumption drops in winter and peaks in March, which does not conform to the actual electric consumption trend.

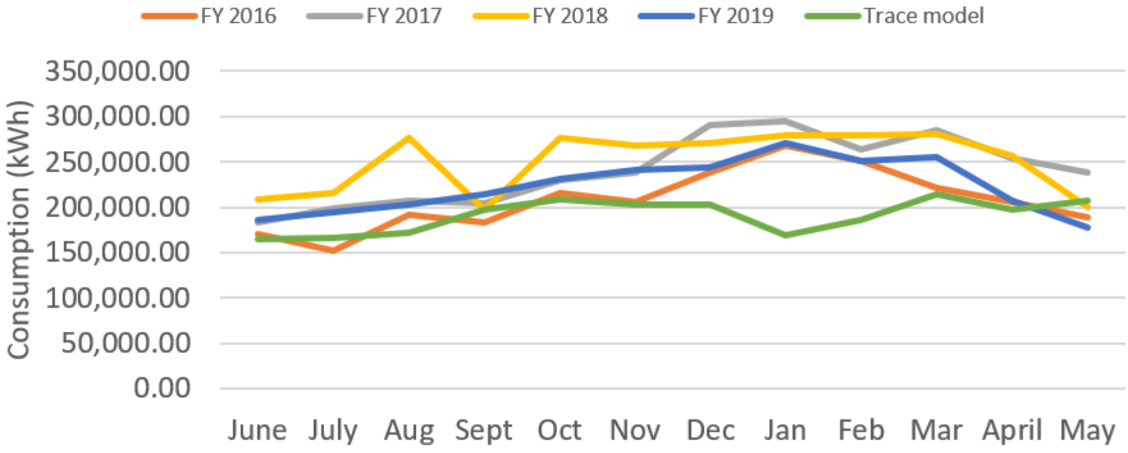


Figure 19: ECE building electricity consumption FY2016-FY2019

3.5.2 Chilled water consumption

The measured monthly chilled water (CHW) consumption of the ECE building over the last four fiscal years illustrates that peak CHW usage occurs in summer between May and August, then usage rapidly drops as the weather temperature decreases, as shown in Figure 20 . The energy TRACE model showed that consumption drops in winter and peaks in summer, which conforms to the actual electric consumption trend.

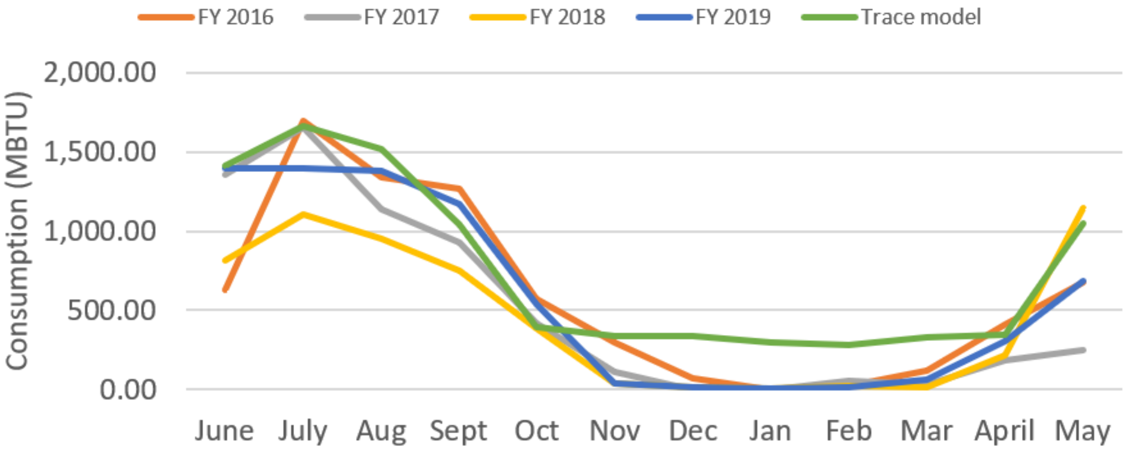


Figure 20: ECE building chilled water consumption FY2016-FY2019

3.5.3 Condensed steam consumption

The measured monthly condensed steam (CS) consumption of the ECE building over the last four fiscal years illustrates that peak CS consumption usage occurs in winter between November and January, as shown in Figure 21. The energy TRACE model showed that consumption peaks in winter and drops in summer, which conforms to the actual electric consumption trend.

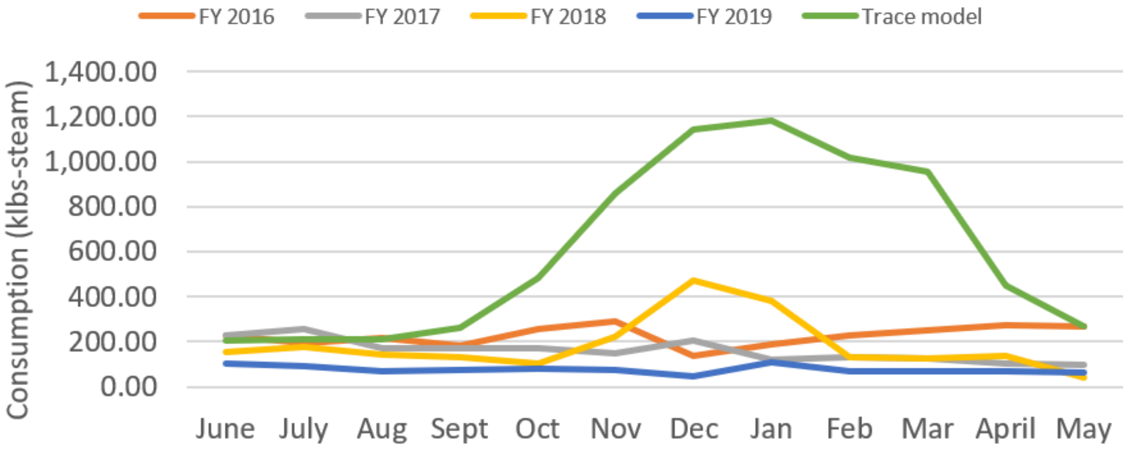


Figure 21: ECE building steam consumption FY2016-FY2019

3.5.4 Energy use intensity of the ECE building

The energy use intensity (EUI) was calculated for all utility consumption, and the TRACE model, as shown in Figure 22. The TRACE model for the ECE building showed a predicted EUI of 96. While actual EUI of FY 2016 to FY2019 was between 71 and 75 with an average 73.5. Hence, the annual metered data for total energy usage shows that measured building performance is better than the predicted model by 31%, as shown in Table 2.

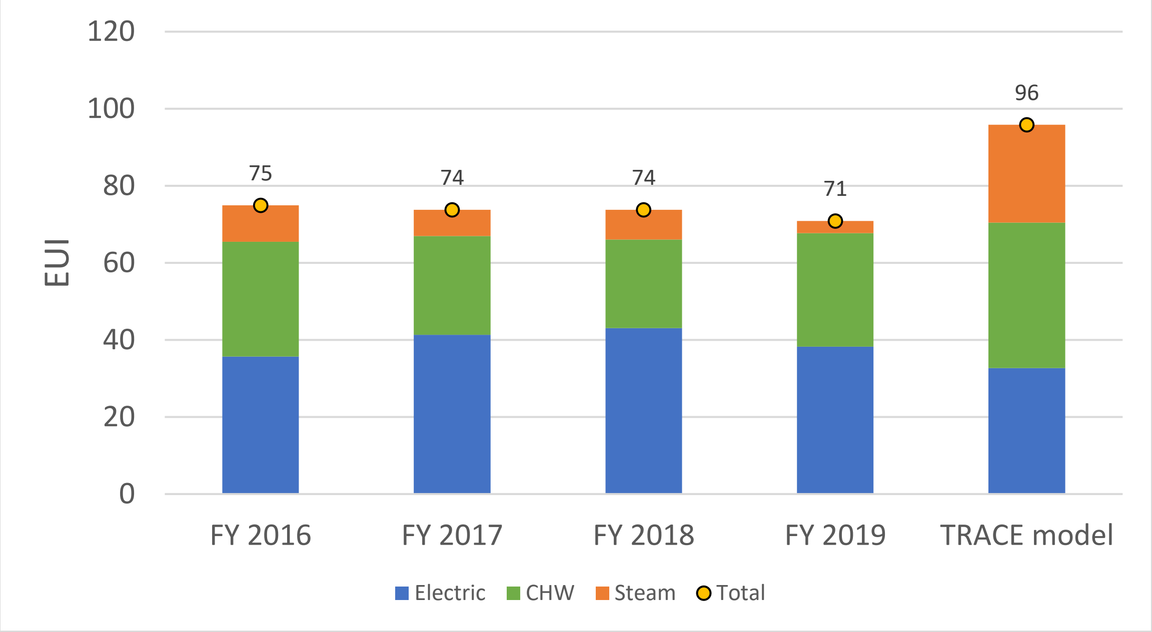


Figure 22: ECE building energy use intensity FY2016 - FY2019

Table 2: ECE building energy use intensity FY2016-FY2019

	FY 2016	FY 2017	FY 2018	FY 2019	Trace model
Electric	36	41	43	38	33
CHW	30	26	23	29	38
Steam	9	7	8	3	25
Total	75	74	74	71	96

3.6 Accuracy of Building Energy Model

This section analyzes the accuracy of the aforementioned building energy model (TRACE) for the ECE building by comparing its monthly predicted energy consumption to its monthly measured values for electricity, CHW, and CS consumption, as shown in Figure 23, Figure 24, Figure 25.

The analysis illustrates that the accuracy of the electric consumption predication of the TRACE model in FY 2016 ranged from 9% (underestimated consumption) to 37% (overestimated consumption) with an average monthly electric usage of 207,632 kWh, FY 2017 ranged from 4% (overestimated consumption) to 42% (overestimated consumption) with an average monthly electric usage of 240,455 kWh, FY 2018 ranged from 3% (underestimated consumption) to 39% (overestimated consumption) with an average monthly electric usage of 250,835 kWh, and FY 2019 ranged from 16% (underestimated consumption) to 37% (overestimated consumption) with an average monthly electric usage of 222,953 kWh, as shown in Table 3. The average monthly electric consumption from FY2016 to FY2019 with reference to the energy model predictions showed that actual consumption was higher than the energy model by 21%, as shown in Figure 23 and Table 6.

Table 3: ECE building electric monthly consumption FY 2016 -FY 2019

	Trace model Electricity (kWh)	**FY 2016**		**FY 2017**		**FY 2018**		**FY 2019**	
		Electricity (kWh)	**Accuracy (%)**	**Electricity (kWh)**	**Accuracy (%)**	**Electricity (kWh)**	**Accuracy (%)**	**Electricity (kWh)**	**Accuracy (%)**
June	164,166	170,570	4%	183,089	10%	209,059	21%	186,293	12%
July	165,657	152,025	9%	198,526	17%	216,231	23%	194,482	15%
Aug	171,583	191,952	11%	207,173	17%	276,852	38%	203,060	16%
Sept	196,503	182,430	8%	203,659	4%	196,852	0%	213,797	8%
Oct	208,539	215,955	3%	229,963	9%	275,941	24%	230,905	10%
Nov	202,172	205,005	1%	238,382	15%	267,822	25%	241,212	16%
Dec	203,491	238,051	15%	290,066	30%	271,328	25%	244,097	17%
Jan	169,316	268,497	37%	294,423	42%	278,860	39%	270,858	37%
Feb	186,043	250,517	26%	263,565	29%	279,099	33%	250,436	26%
Mar	213,689	221,424	3%	284,652	25%	281,295	24%	255,738	16%
April	197,141	206,120	4%	253,119	22%	257,215	23%	207,344	5%
May	206,442	189,039	9%	238,839	14%	199,465	3%	177,214	16%
Average	**190,395**	**207,632**	**8%**	**240,455**	**21%**	**250,835**	**24%**	**222,953**	**15%**

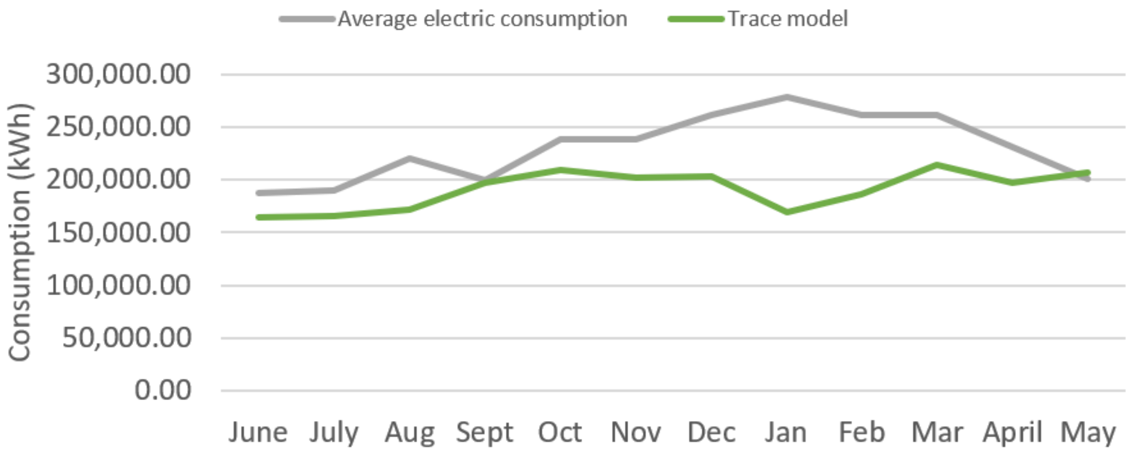


Figure 23: ECE building average electric consumption vs. energy load (TRACE model)

The analysis also illustrates that the accuracy of the CHW consumption predication of the TRACE model in FY 2016 was 27% with average monthly CHW usage of 592 MBTU, FY 2017 was 47% with average monthly CHW usage of 511 MBTU, FY 2018 was 65% % with average monthly CHW usage of 456 MBTU, and FY 2019 was 29% with average monthly CHW usage of 584 MBTU, as shown in Table 4. The average monthly CHW consumption from FY2016 to FY2019 with reference to the energy model predictions showed that actual consumption was lower than the energy model by 29%, as shown in Figure 24 and Table 6.

Table 4: ECE building CHW monthly consumption FY 2016 -FY 2019

	Trace model CHW (MBTU)	**FY 2016**		**FY 2017**		**FY 2018**		**FY 2019**	
		CHW (MBTU)	**Accuracy (%)**	**CHW (MBTU)**	**Accuracy (%)**	**CHW (MBTU)**	**Accuracy (%)**	**CHW (MBTU)**	**Accuracy (%)**
June	1,416	630	125%	1,355	5%	812	74%	1,397	1%
July	1,660	1,692	2%	1,653	0%	1,107	50%	1,394	19%
Aug	1,517	1,341	13%	1,142	33%	949	60%	1,383	10%
Sept	1,039	1,267	18%	932	12%	754	38%	1,166	11%
Oct	395	569	30%	418	5%	389	2%	540	27%
Nov	335	297	13%	109	208%	38	792%	39	764%
Dec	334	69	385%	0	596325%	13	2484%	17	1827%
Jan	300	1	47668%	0	136473%	6	4663%	8	3903%
Feb	285	25	1055%	55	418%	21	1288%	11	2527%
Mar	329	121	172%	29	1041%	17	1845%	62	427%
April	346	411	16%	181	90%	219	57%	302	15%
May	1,051	681	54%	253	316%	1,143	8%	685	53%
Average	**751**	**592**	**27%**	**511**	**47%**	**456**	**65%**	**584**	**29%**

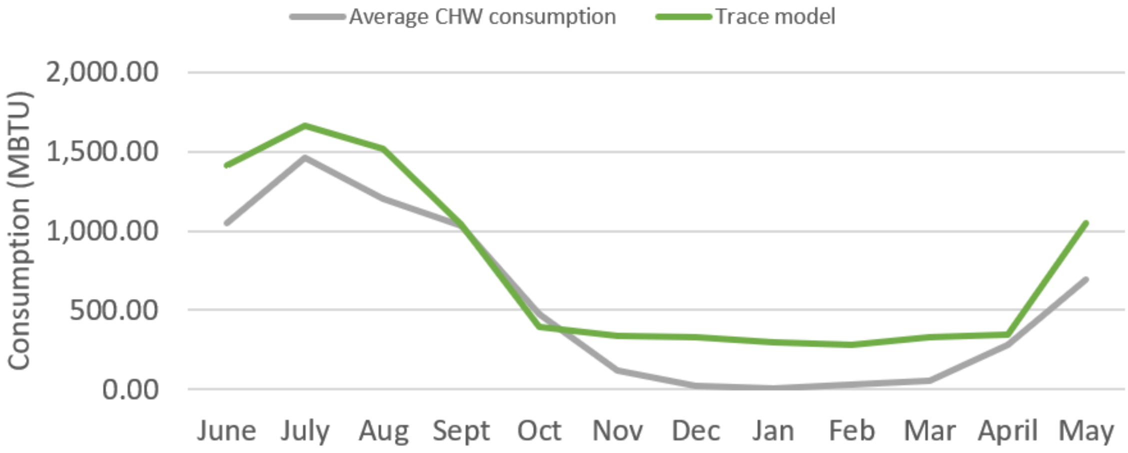


Figure 24: ECE building average CHW consumption vs energy load (TRACE model)

The analysis illustrates that the accuracy of the CS consumption predication of the TRACE model in FY 2016 was 167% with average monthly CS usage of 226 klbs-steam, FY 2017 was 275% with average monthly CS usage of 161 klbs-steam, FY 2018 was 227% with average monthly CS usage of 185 klbs-steam, and FY 2019 was 688% with average monthly CS usage of 77 klbs-steam, as shown in Table 5. The average monthly CS consumption from FY2016 to FY2019 with reference to the energy model predictions showed that actual consumption was lower than the energy model by 73%, as shown in Figure 25 and Table 6.

Table 5: ECE building CS monthly consumption FY 2016 -FY 2019

	Trace model CS (klbs)	FY 2016		FY 2017		FY 2018		FY 2019	
		CS (klbs-steam)	Accuracy (%)	CS (klbs-steam)	Accuracy (%)	CS (klbs-steam)	Accuracy (%)	CS (klbs-steam)	Accuracy (%)
June	205	227	10%	227	10%	157	31%	106	94%
July	209	195	7%	258	19%	175	19%	93	126%
Aug	210	214	2%	174	21%	141	49%	71	195%
Sept	262	181	45%	174	50%	129	103%	74	256%
Oct	485	257	89%	170	185%	101	382%	81	497%
Nov	859	292	194%	147	485%	223	285%	73	1072%
Dec	1,144	135	750%	208	451%	473	142%	44	2515%
Jan	1,183	191	519%	122	866%	382	209%	111	966%
Feb	1,016	230	342%	130	679%	132	672%	68	1400%
Mar	958	250	283%	123	677%	128	647%	68	1317%
April	448	276	62%	104	332%	135	233%	67	571%
May	268	267	0%	96	180%	43	525%	66	308%
Average	**604**	**226**	**167%**	**161**	**275%**	**185**	**227%**	**77**	**688%**

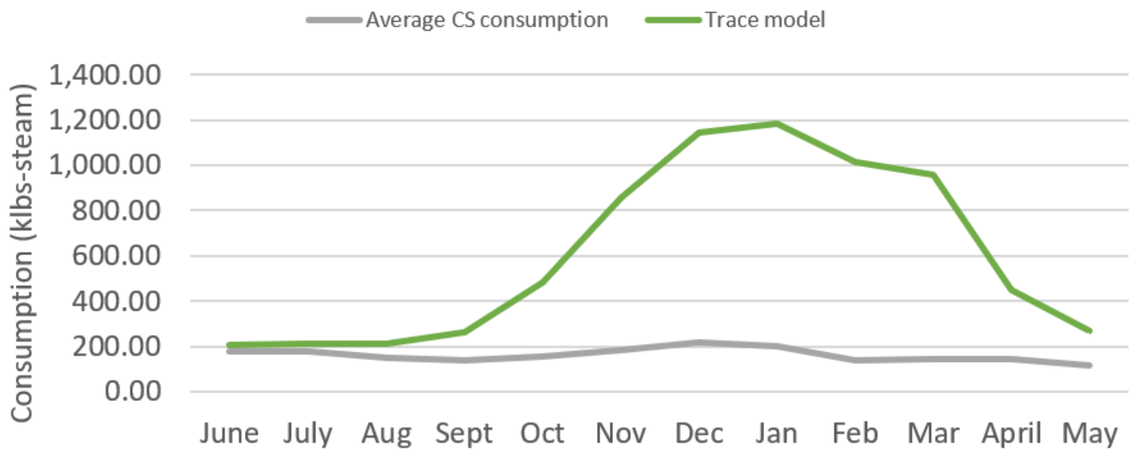


Figure 25: ECE building average CS consumption vs. energy load (TRACE model)

Table 6: Actual vs predicted energy consumption

Utility	Average Actual Consumption (FY2016 - FY2019)	Average Predicted Consumption (TRACE model)	Percentage Difference	Model Accuracy
Electricity (kWh)	230,469	190,395	21%	Underestimated
Chilled Water (MBTU)	535	751	29%	Overestimated
Steam (klbs-steam)	162	604	73%	Overestimated

3.7 Generated Renewable Energy

On-site photovoltaic (PV) solar panels are the only renewable energy source incorporated in the ECE building. The panels are installed facing south at an angle of 32° to maximize their energy collection. About 950 PV panels were installed on the building's rooftop. The panels are divided into several arrays, including 60 PV panels assigned to research purposes. The PV panels are able to produce approximately 275 kW at their highest efficiency. The installed PV panels convert the energy collected into AC electricity directly without the use of inverters, which makes them more efficient. Figure 26 shows an image taken by a drone of the ECE building roof with on-site PV panels.

Figure 26: Drone shot of the rooftop solar panels

Data of generated energy was collected from 2 meters (1) 0409-E75 and (2) 0409-E77. The available data from the meters covers only 3 months starting from their initial operation in April to the current month of July 2019. A preliminary analysis of this limited data show that the energy generated from the PV solar panels covers an average of almost 12% of the building electricity consumption, as shown in Table 7 and Figure 27.

Table 7: ECE building electric consumption offset by onsite renewable energy generation

Period	Onsite energy generation (kWh)	Electric energy consumption (kWh)	Energy offset
April 20th - July 1st , 2019	15,255	130,720	12%

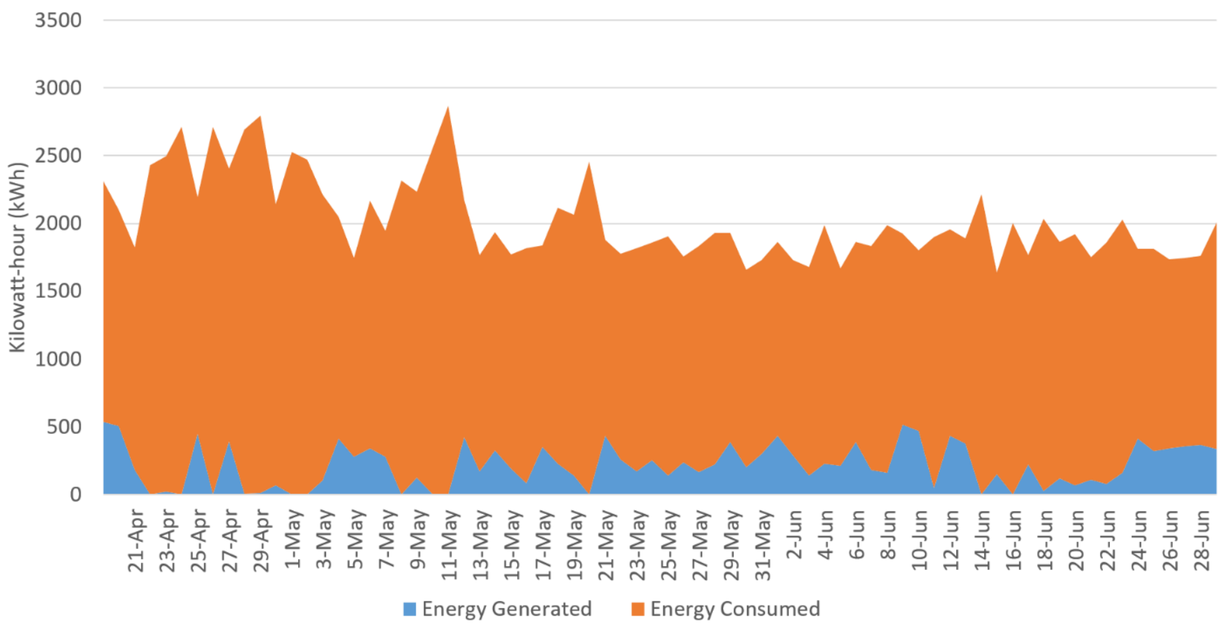


Figure 27: Electric consumption vs. onsite electric production

In addition to the rooftop PV panels, the initial energy design of the ECE building included the installation of offsite PV panels on the nearby parking garage building. This initial design was planned to generate an additional 1.2 MW. This initial design however was not implemented due to two design errors: (1) the structural design of the posts carrying the PV panels did not consider Illinois wind loads, and (2) the initial electrical design did not consider the losses in the connection between the ECE building and the parking garage. The structural design error resulted in a budget increase of 60%, from $3.68 million (according to the feasibility study) to almost $6m, for the installation of these offsite PV panels, which made this project cost prohibitive.

3.8 Summary

The review and analysis of the ECE building, presented in this chapter, covered (1) the energy consumption reduction measures attained by incorporating active and passive design approaches, (2) building design modelling, (3) an analysis of measured actual energy consumption and the accuracy of the building energy model, and (4) an analysis of the performance of the on-site renewable energy.

CHAPTER 4 - ENERGY EFFICIENCY IMPROVEMENTS FOR CASE STUDY

4.1 Introduction

This chapter focuses on (1) investigating the causes that prevented the analyzed case study in the previous chapter from accomplishing its zero energy goal, (2) develop recommendations to enhance its current performance; and (3) identify lessons learned that could be used to improve the design and construction of future similar ZEB.

4.2 Causes Preventing Accomplishment of Zero Energy Goal

Based on the aforementioned in-depth analysis of the case study of the ECE building, two main causes were identified that have prevented it from accomplishing its zero energy goal. These two main causes are (1) underestimating the building energy consumption during the design phase by the developed building energy model (TRACE), and (2) overestimating the generated renewable energy by the building. These two main causes are discussed in more details in the following sections.

4.2.1 Underestimating building energy consumption

In order to investigate the causes of underestimating the building energy consumption during the design phase by the developed building energy model (TRACE), an in-depth analysis was conducted to identify the causes of accuracy differences between the model and the actual measured consumption (shown in Table 6).

The aforementioned passive and active energy efficient features were accounted for in the developed energy building model for the ECE building. The modeling of these building energy efficient features is grouped into the following sections the focus on: (1) building envelope, (2) lighting, and (3) mechanical systems.

4.2.2 Building design model input analysis

Building envelope

Roof

The drawings and the project manual did not specify minimum thermal resistance (R-Value) for the insulation. However, it was specified as “polyisocyanurate board insulation: ASTM C 1289, Type II, Class I, Grade 3 (25 psi), felt or glass-fiber mat facer on both major surfaces,” with a minimum of two layers 2” thick with 1/2-inch glass-mat, water-resistant gypsum cover board and substrate. Accordingly, the estimated total effective assembly thermal resistance (R-value) and thermal transmittance (U-factor) for the specified roof construction are R-23 and U-0.043. In the developed building energy model, R-6 and U-0.040 thermal resistance and thermal transmittance were used respectively. A summary of this analysis is illustrated in Table 8.

Exterior walls

In the drawings and the project manual the exterior wall insulation was specified as “exterior wall insulation is foil-faced polyisocyanurate board”. However, it did not specify a thermal resistance it. A typical exterior wall requires a “minimum of R-26” for the two layers of 2” thick insulation. Product datasheet for the specified insulation, Thermax, indicates that the 2” thick boards equal R-13 so two layers would be R-26 (DOW, 2009). Accordingly, the estimated total effective assembly thermal resistance (R-value) and thermal transmittance (U-factor) for the specified exterior wall construction is R-30.5 and U-0.033. In the developed building energy model, an assembly U-0.032 was used, which is consistent with the calculated U-factor based on the construction documents. A summary of this analysis is illustrated in Table 8.

Doors and windows

In the construction documents, the thermal transmittance and solar heat gain coefficient were estimated to be U-0.45 and SHGC-0.32 respectively. In the developed building energy model, thermal transmittance and solar heat gain coefficient of U-0.39 and SHGC-0.28 were used respectively, for the exterior window. Which is an overestimation of the specified window performance in the construction documents. A summary of this analysis is illustrated in Table 8.

Table 8: Energy model analysis summary - Building envelope

Building element	Proposed building reference (construction documents)	Proposed energy model
Roof	U-0.043	U-0.040
Exterior Walls	U-0.033	U-0.032
Windows and doors	U-0.033	U-0.032
	SHGC-0.32	SHGC-0.28

Lighting

A comprehensive LPD calculation was performed based on the lighting layouts and fixture schedule. The LPD for whole building area was estimated to be 0.70 W/sf. In the developed building energy model, LPD value used was 0.70 W/sf for the majority of the building spaces with some spaces using 0.80 W/sf. The overall building LPD used in the proposed energy model was 0.76 W/sf. A summary of this analysis is illustrated in Table 9.

Table 9: Energy model analysis summary - Lighting

Building element	Baseline reference (ASHRAE 90.1-2007)	Baseline energy model	Proposed building reference (construction documents)	Proposed energy model
Lighting	Maximum: 1.2 W/sf	1.2 W/sf	0.70 W/sf	0.76 W/sf

Mechanical systems

The mechanical systems of the heat recovery system, and the chilled beams system were not modeled in the proposed building model.

The proposed building model reasonably modeled the building envelope with reference to the construction documents. However, it used an area of 199,455 net square feet (nsf) which is less than the actual area of the ECE building by almost 17%. Also, some systems such as the heat recovery chiller and chilled beams which provide the primary heating and cooling loads of the building were not accurately modeled in the TRACE software, and thus results from the TRACE energy model are not very accurate. The energy model underestimated the building's electric usage and overestimated the steam and chilled water consumption.

4.2.3 Overestimating onsite generated renewable energy

The current onsite renewable energy is not sufficient to offset the ECE building's electric consumption. The early results of the on-site rooftop renewable energy show that it is physically impossible for ECE building to reach zero energy over a period of a year using the rooftop PV panels only. The area of Urbana at Illinois has an average of 3.14 peak sun hours for solar production daily, as shown in Figure 28. Accordingly, the annual production of the rooftop solar panels can be estimated to be 343,830 kWh which can offset approximately 15% of the average annual consumption.

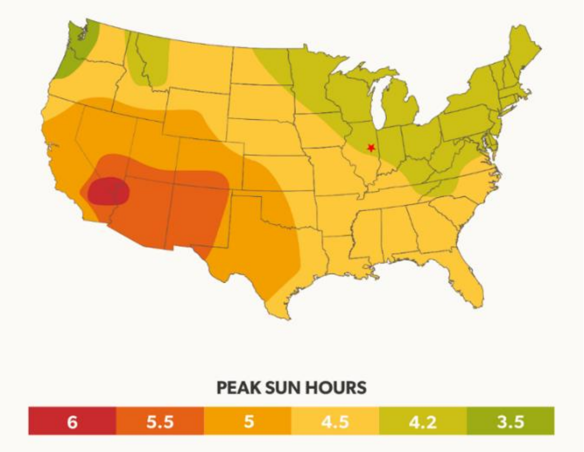


Figure 28: U.S. solar insolation map

There are multiple types of renewable energy sources that can be utilized to balance the energy consumption of the building to achieve the zero energy goal. When other renewable energy resources are explored, such as wind energy, it was found that adding small wind turbines onsite is not effective, since the wind resources in Illinois are marginal, as shown in Figure 29. Additionally, it is structurally challenging and requires a sophisticated structural analysis to study the constructability of small wind turbines on top of the building.

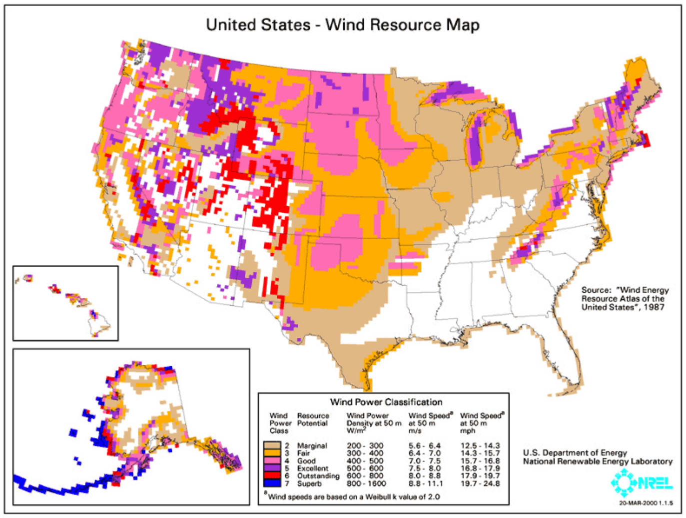


Figure 29: U.S. wind resource (NREL)

4.3 Recommendations for Case Study

In order to identify potential energy efficiency improvement to the ECE building to advance its design goal of achieving zero energy performance, structured personal interviews were conducted with four stakeholders of ECE building. Four separate interviews were conducted with stakeholders who were involved in the planning, design, construction and operation of the ECE building.

The first interview was conducted with Professor Krein who was involved in the planning, design, construction, and operation of this project. He is the chair of the ECE new building committee He mentioned that the main goals of the project were to consolidate the department, address its critical space needs, and enhance its instructional and research capabilities. During the planning phase, a number of the stakeholders and future occupants were interviewed to consider their needs and expectations in the new building plan. These needs were placed in the context of architectural design, location, costs, energy efficiency, and sustainability constraints. Regarding the challenges during the design and construction of the ECE building, Professor Krein mentioned that having a design-build approach could have made the process easier. However, to overcome this, efforts were put to coordinate and facilitate communication between the new building committee, the design team (Smithgroup and KJWW), and the main contractor (Williams Brothers Construction). For example, an engineer from KJWW, the mechanical and electrical engineering consultant was assigned to the project during the construction phase to assure construction and design compatibility. As for targeting zero energy, Professor Krein explained that it was crucial for project success to unify zero energy objectives for the project team by clearly outlining the adopted ZEB definition. Professor Krein elaborated that the consensus on this project was to account for the energy use by only considering what the meters recorded as energy input to the building. Accordingly, the efficiencies of the campus central plant were not considered in the calculations during the design phase. Professor Krein also added that the energy efficient measures incorporated in the ECE building included (1) heat exchange system that uses energy from already heated or cooled air before it is pumped out of the building, (2) ventilation system in the auditorium that pumps heated or chilled air directly to occupants rather than ventilating the entire space, (3) building envelope that utilizes terra cotta for insulation, and (4) LED lights and high efficiency fluorescent lamps for artificial lighting. Professor Krein mentioned the importance of dealing with the project as a system and realize the interaction between the subsystems and their efficiencies when they are operated together. He concluded that the department of ECE is determined to reach the zero energy goal while recognizing the challenges and the extended timeframe that a complex building such as the ECE building requires to adjust its system operations.

The second interview was conducted with Ms. Joyce Mast, an ECE new building committee member, she explained that prior moving into the new ECE building; the department had raised awareness about the new building energy-efficient features and how occupants' behavior can support energy usage reduction. Ms. Mast elaborated that the main challenge is to make people aware of their energy usage. She suggested that the ECE building energy performance can be improved by utilizing two touch-screen kiosks programmed to interact with students to improve their energy awareness. She suggested that these screens can be programmed to ask a student whether they live in an apartment, a house, or a dorm then give them information about the energy required to power different home appliances such as a hairdryer, a refrigerator, or different kinds of light bulbs. The use of this suggested interactive screen has the potential to encourage students to think about how often they use these devices, and when they use them to illustrate the higher cost of peak power.

A third interview was conducted with Mrs. Sanja Koric, a mechanical-controls engineer at the department of facilities and services. Mrs. Koric stated that the main challenge that confronted the project during the design phase was the selection process of the energy efficient mechanical and electrical systems and the sustainable and energy efficient materials. The addition of energy wheels inside air handling units and a heat recovery chiller to the mechanical design of the building was beneficial towards achieving the zero energy goal. Mrs. Koric also stated that there are additional opportunities to enhance the energy efficiency of the building by implementing alternative systems such as photovoltaic window systems, since the building has large glass surfaces that could positively contribute to energy generation . She also suggested that water conservation can be enhanced using “gray water systems”, and a geothermal system can be utilized to generate energy for the perimeter systems.

A fourth interview was conducted with Mr. Andy Robinson, a direct control specialist at the department of facilities and services and a member of the retro-commissioning team. He was part of the team that performed retro-commissioning (RCx) at the ECE building at the beginning of

2019. He mentioned that RCx is commissioning for existing buildings, and it should be implemented every 3 to 5 years. RCx is a systematic process of identifying current operational issues and creating a plan to fix them, starting with items with the highest savings. The objective of the process is to improve the performance of the building's subsystems and their coordination together as a system.

RCx process begins with an in-depth evaluation of the building's operational performance, including both mechanical and electrical systems, to develop and compile a list of possible improvements. Then a cost analysis is performed to select the items with the highest savings. Typical RCx procedures include improvements to the control system, calibrations, setpoint changes, and other low-cost improvements. Mr. Robinson mentioned also that RCx was performed by the facilities and services department at the University of Illinois. The team evaluated the performance of the main mechanical and electrical systems, including heat recovery chillers, chilled beams, and occupancy sensors. Then a list of issues was identified, studied, and submitted to the facilities and services department by the ECE building facility manager. A list of items that need to be addressed was created, and items were prioritized based on the highest possible savings, followed by the lowest cost of the retrofit and the easiest fixes. The list included (1) adding insulation to the steam and hot water lines at water heaters, (2) sealing up the ductwork connection to the chilled beam units, (3) fixing an error in the process of the heat recovery chillers that causes the pumping back of warm water to the central campus chilled water loop, and (4) fixing the heat recovery loop for AHU-6 that was not working. The RCx process took around 3 months, and it cost about $300,000. Mr. Robinson explained further that the RCx resulted in a reduction in energy consumption by almost 5% since FY 2016, and reduction in the utility bills by 16.5% since FY 2016.

Based on the aforementioned conducted interviews, literature review, and case study analysis, several recommendations were identified to improve the energy efficiency of the ECE building and advance its initial design goal of achieving zero energy performance. These identified recommendations need to be further studied to analyze their technical and financial feasibility. The recommendations are grouped into two main categories that focus on (1) reducing building energy consumption, and (2) increasing its generated renewable energy and summarized in Table 10.

Table 10: Recommendations to the ECE building

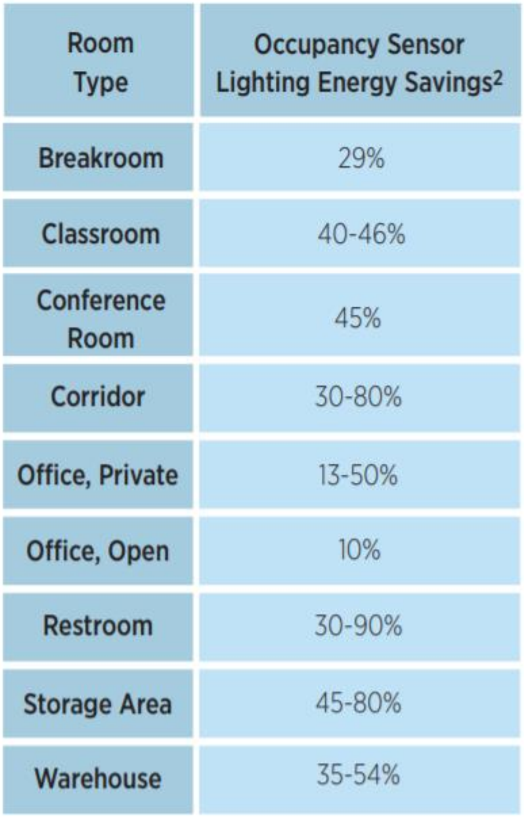
Approach	Recommendation	Methodology
Reducing building energy consumption	Upgrading occupancy sensors	Change currently installed occupancy sensors with ceiling mounted sensors.
	Demand-controlled air filtration for cleanroom	Install particle counter in cleanroom
	Increasing Occupants awareness	Interactive screens (eco-feedback)
		Gamification
	Increase water conservation	Incorporate gray water systems
Increasing building generated renewable energy	Increase onsite generated energy	Install photovoltaic window systems
	Utilize virtual net metering (VNM) (offsite)	Purchase or subscribe in a community solar plant connected to the ECE building grid
	Utilize renewable energy certificates (RECs) (offsite)	Purchase RECs

4.3.1 Reducing building energy consumption

Upgrading occupancy sensors

Based on the conducted literature review, upgrading the existing sensors in the ECE building can result in additional energy savings. Per the ECE building project specifications, the occupancy sensors installed in the majority of the classrooms, labs, and offices are wall mounted sensors that only control lighting based on space occupation. A retrofit would be exchanging wall mounted sensors with infrared ceiling sensors, that has a wider sensing area and control the ventilation system as well as the lighting based on space occupation (DOE, 2016). The Department of Energy reported that the celling sensor could enhance energy saving depending on room type, as shown in Table 11.

Table 11: Energy savings from occupancy sensors (DOE, 2016)



Room Type	Occupancy Sensor Lighting Energy Savings[2]
Breakroom	29%
Classroom	40-46%
Conference Room	45%
Corridor	30-80%
Office, Private	13-50%
Office, Open	10%
Restroom	30-90%
Storage Area	45-80%
Warehouse	35-54%

The cooling and heating load in the classrooms, lecture halls, and meeting rooms are based on full occupancy of the space. This consumes more energy than required when the planned maximum number of occupants are not present. Installing a sensor with occupant counting capabilities in these spaces will save energy by adjusting the cooling or heating load based on present occupants rather than the room's capacity; Thereby, using energy only when needed and maintain occupants comfort by not over heating or cooling the occupied space. Studies have researched different methodologies for occupant counting based on the working environment and flow of occupants

(Zhang, Liu, Lutes, & Brambley, 2013), (Kuutti, Blomqvist, & Sepponen, 2014), and (Ekwevugbe, Brown, Pakka, & Fan, 2016).

Demand-controlled air filtration for cleanroom

One of the most energy exhausting spaces in the building is the cleanroom. It requires the ventilation system to run at all times and continuously filter the air to meet the minimum air quality requirements of the cleanroom. However, the ventilation system is operating 24 hours a day, 7 days a week, whether air filtration is necessary or not. A typical daily particle count profile of a 1000-cleanroom is shown in Figure 30 (Kircher, Shi, Patil, & Zhang, 2010). This illustrates that continuous filtration is unnecessary, and filtration can be efficiently utilized during peak particle concentration periods shown in Figure 30. This efficient modifications in the operation of the ventilation system can result in big energy savings. A study showed that filtration controlled by demand had shown 37–40% reductions in fan energy consumption when cleanroom fan speeds are modulated based on particle concentrations (Kircher et al., 2010).

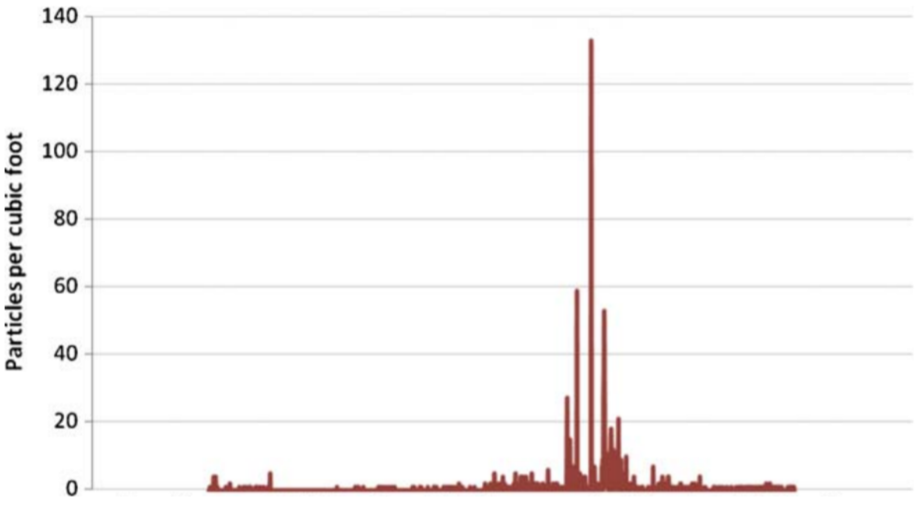


Figure 30: Daily particle count profile for a 1000-cleanroom

4.3.2 Increase occupant’s awareness

Occupants constitute a significant factor that influences energy consumption and contributes to the uncertainties in energy modeling and simulation. A number of studies reported that raising awareness to improve occupants’ behavior increases the efficiency of energy usage (Jang & Kang, 2016), (Karatas, Stoiko, & Menassa, 2016),(Kazmi, D’Oca, Delmastro, Lodeweyckx, & Corgnati, 2016). Raising occupants awareness can be accomplished using (1) eco-feedback (Kircher et al., 2010) that was suggested in the aforementioned interviews by Ms. Mast, and (2) gamification that uses features of games to accomplish a real-world objective (Grossberg & Wolfson, 2015), (Du, Feng, & Zhou, 2014). The objective of the game is to reduce energy consumption and the winner can get be recognized by the department or receive an actual reward.

4.3.3 Geothermal systems

In the abovementioned interviews, Mrs. Koric suggested incorporating a geothermal system to further reduce energy consumption in the ECE building. Geothermal systems use heat from underground hot water to provide heat for the building (J. Lund, Sanner, Rybach, Curtis, & Hellström, 2004). The DOE stated in a report published in 2004 on energy saving benefits of utilizing a geothermal system to reduce heating peak loads that geothermal systems can save energy by 80% more than conventional fossil fuels (DOE, 2004).

4.3.4 Water conservation

In the abovementioned interviews, Mrs. Koric suggested utilizing gray water systems to conserve water usage at the ECE building. Additional savings can be realized by collecting rainwater water from sinks recycling onsite so it can be reused for nondrinking purposes. This system can lead to a 50% reduction in water consumption compared to standard water systems (Schuetze, Lee, & Lee, 2013).

4.3.5 Increasing building generated renewable energy

Photovoltaic window system

The entire south side of the ECE building had windows. These windows can be exchanged by photovoltaic window panels which are able to let daylight into the building while capturing solar energy and converting it into electricity. Increasing the source of on-site renewable energy is fundamental for ECE building to achieve zero energy goals. However, it is physically challenging to add an onsite renewable source. Thus, renewable energy certificates or virtual net metering (VNM) could be possible alternatives for the building to achieve its zero energy goals.

Virtual net metering

VNM, is a billing system for community sola which is an offsite solar energy alternative that can be on ownership or subscription basis. Community solar allows building owners to purchase part of a solar plant that is connected to the building’s grid that can provide energy as much as the building’s maximum average annual consumption (Farrell, 2015). The output of these PV panels is credited from the monthly electricity through VNM and thus offsetting the energy consumption (Energy Sage, 2018). Only a few states are allowed to use virtual net metering, including the state of Illinois, an opportunity for the ECE building to reach its zero energy goal (Farrell, 2015).

Renewable energy certificates

The U.S. DOE definition of ZEB and its variations do not allow offsite renewable energy to be used to fully offset the actual annual energy consumption and do not allow renewable electricity to be purchased through renewable energy certificates (RECs) for zero energy calculations. However, the DOE added a variation to ZEB, REC-ZEB, and defined it as “ An energy-efficient building where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy plus acquired Renewable Energy Certificates (RECs).” (DOE, 2015a). This variation was added to allow laboratory buildings, that are energy intensive, such as the ECE building with limited area for onsite renewable energy generation, to meet zero energy by purchasing REC. However, it can only be verified as REC-ZEB if it can confirm that the total annual consumption of the building is offset by the onsite renewable energy and the RECs.

4.4 Lessons Learned for Zero Energy Buildings

Based on the aforementioned literature review, case study analysis, and interviews with different stakeholders, various lessons learned from the project were identified than can be used by future adopters of a similar zero energy building. These lessons learned are grouped in three different categories (1) project planning, (2) energy consumption reduction, and (3) onsite renewable energy. A summary of the identified lessons learned is shown in Table 12.

Table 12: Summary of lessons learned for ZEB

Project planning	Extensive feasibility study
	Delivery method selection
	Contract type selection
Energy usage reduction	Accuracy of building energy model
	Selection of onsite renewable energy source
	Significance of occupant's behavior
Onsite renewable energy	Design accuracy of onsite renewable energy
	Selection of energy efficient systems and materials

4.4.1 Project planning

Based on the aforementioned interviews with the stakeholders of the ECE building, analysis and literature review, performing an extensive and detailed feasibility studies prior to the commencement of the detailed design and construction phases have the potential of ensuring project successful completion by guaranteeing that the owner will be able to allocate all the required funding to finance different project phases.

The design-build delivery method has the potential to reduce construction costs by an average of 6% less, increase construction speed by an average of 12%, and complete project delivery faster by an average of 33% (DOE, 2004). Additionally, coupling a design-build approach with clear and prioritized performance requirements can enhance project performance and increase contractor's accountability. A successful example of this approach is the case study covered in the abovementioned literature review, the Research Support Facility owned by the DOE in Golden, Colorado. This approach makes one entity accountable and leads to a smoother and faster construction process. Also, contract type can affect the success of the project. For example, in a performance based design-build process, the owner's risks are less than the design-bid-build scenario. In the design-builder scenario, once the contract is signed, achieving the owner's performance goals becomes the design-builder responsibility. Hence, the owner's risk is reduced compared to a design-bid-build scenario.

4.4.2 Reducing energy consumption

Based on the aforementioned interviews with the stakeholders of the ECE building, analysis and literature review, rigorous research to identify the building's function, the purpose of every space, and the energy needs of the building is essential to the design and energy model simulation accuracy. In a building similar to the ECE, heating, cooling and lighting are the most energy consuming end uses, and thus, appropriate selection of building orientation, envelope, efficient systems that are capable of fulfilling the building's requirements without sacrificing occupant's comfort or energy goals is crucial for project's success.

The energy model accuracy depends on the selection of the software and its modeling capabilities for all building subsystems and their relationship as they operation as one system rather than individual systems. The energy model verifies the energy savings realized by the abovementioned selection of energy efficient systems.

Considering occupant's behavior can significantly affect the building's energy consumption. Raising awareness before and during occupancy and using different strategies such as eco-feedback and gamification can modify the building's performance. As an education building, the majority of the building's occupants are students, and visiting scholars. Those occupants are not constant and therefore making raising awareness on energy savings and smart energy behavior a challenge. However, raising awareness to improve occupant's behavior remains crucial to decreasing energy usage. Thus, more energy should be exerted on keeping occupants informed of the building's energy goals and strategies, to contribute to achieving them.

4.4.3 Onsite renewable energy

Design and calculations of onsite renewable energy are essential to ensure that the maximum possible generation is able to offset predicted energy loads. The selection of the on-site renewables used to achieve ZEB depends on the local climate, building size, characteristics and site location. The most common types of technologies used for on-site renewable power are photovoltaics (PV) and wind turbines. The wind turbines used for commercial buildings would be considered smallscale wind turbines. The choice of the type of turbine is important to maximize energy production. PV has a range of efficiencies and module types. The output of a PV system can be predicted through the use of solar-insolation data for the area where the site is located. It is important to factor in the overall system efficiency when calculating the predicted power output of renewable technologies. The type of solar panels used in the ECE building does not require conversions between dc and ac power, which saves efficiency losses that otherwise are lost in the conversion.

4.5 Summary

In this chapter, (1) causes preventing the ECE building from achieving its zero energy goal were investigated and analyzed, (2) highlights of interviews with different stakeholders are presented, (3) a list of recommendations to enhance the current energy performance in an attempt to advance the ECE building to achieve its zero energy goal, and (4) lessons learned were identified for the use of future adopters.

CHAPTER 5 - CONCLUSIONS

5.1 Conclusions

The present research study focused on analyzing the performance of a large education building that was designed to achieve zero energy performance. and investigating challenges confronting the building from attaining its zero energy goal. The main objectives were to (1) conduct a comprehensive literature review of the current practices and latest research conducted on zero energy buildings; (2) evaluate the performance of a large education building, that was planned to be the largest ZEB in the U.S., as a case study, to analyze the challenges confronting its design and construction; and (3) investigate the causes that prevented the analyzed case study from accomplishing its zero-energy goal, develop recommendations to enhance its current performance; and identify lessons learned that could be used to improve the design and construction of future similar ZEB.

First, a comprehensive literature review was performed to identify the latest research on (1) definitions, and approaches of ZEB adopted in the U.S. and internationally, (2) energy efficient features utilized in ZEB, (3) role of renewable energy in ZEB, and (4) a successful case study of a large commercial building in Golden, Colorado.

Second, A case study of the ECE building was studied and presented. Data from construction documents, energy models, energy meters measuring energy consumption, and onsite energy generation were collected and analyzed to evaluate its performance and to analyze challenges confronting it from achieving zero energy building performance.

Third, causes that prevented the analyzed case study from accomplishing its zero energy goal, recommendations to enhance current building performance were investigated, and a number of lessons learned were identified, to be used to improve the design and construction of future similar ZEB.

Achieving zero energy for a multi-story, large, energy intensive, teaching, and research building such as the ECE building is challenging. NREL and DOE published a report in 2007 that assessed the potential for commercial buildings in the U.S. to achieve zero energy (Griffith et al., 2007). The report included predictions of the percentage of buildings to attain zero energy by 2025 based on the number of stories. Only 0-3 % of four-story commercial buildings are predicted to achieve zero energy by 2025, as shown in Figure 31. Thus, rigorous planning to avoid design is required to achieve this challenging zero energy goal in a multi-story commercial or educational building.

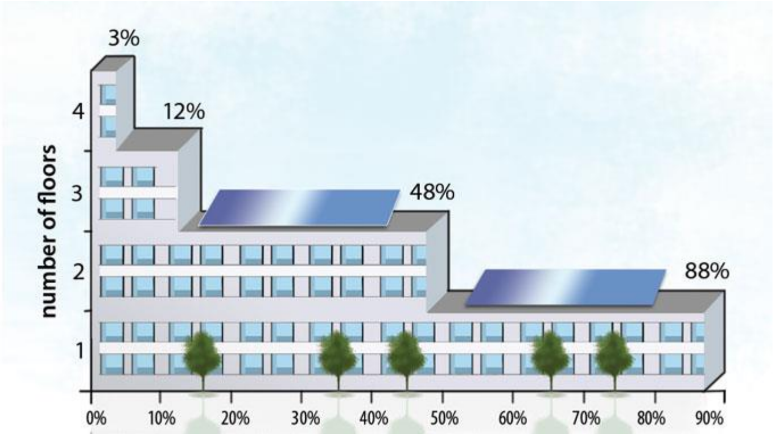


Figure 31: Percentage of U.S. buildings by floor area that could achieve zero energy by 2025 as a function of the number of floors, (Griffith, 2007)

5.2 Future Research Work

Based on the findings of this study, a number of future research areas that need further investigation have been identified. These identified future research areas are:

1. Conducting detailed feasibility studies to analyze the technical and financial feasibility of the aforementioned recommendations to improve the energy efficiency of the ECE building and enable it to achieve its design goal of achieving zero energy performance with the least additional cost.

2. Developing practical optimization models that can support project planners and designers in identifying optimum and cost-effective combinations of a) energy efficient measures that minimize the energy consumption of the building, and b) renewable energy sources that can be used to offset the building energy consumption and achieve zero or near zero energy performance

3. Investigating methods to further increase the energy efficiency of equipment and plug loads.

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