LIFE CYCLE COST ANALYSIS OF AN ENERGY EFFICIENT RESIDENTIAL UNIT

by

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I dedicate this book to my inspiration, my support – my parents

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ABSTRACT

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The residential building sector is one of the most energy intensive sectors in today's civilization. With population growth and a rise in number of homeowners the effect is bound to worsen. A wave of green and sustainable strategies is on the rise hoping to moderate some of the negative effect on the environment. From embracing renewable sources of energy as an alternative to fossil fuels, to improving existing home systems to become more efficient, the construction industry is evolving into becoming more energy conscious. One of the biggest obstacles to this wave is a lack of awareness and a fear of initial costs among contractors, homeowners and clients alike. This research will use Life Cycle Cost Analysis on a varying combination of residential energy systems and the researcher hopes to establish the tradeoff between initial investment and long-term benefits. The case being considered is a residence located in Indiana, US. Using past and current utility bills and energy simulation data of different energy consuming systems in the residence over its lifetime, economic models are generated. This research establishes that a combination of passive and active energy conservation measures results in the lowest life cycle cost. The study will be beneficial for further research and as a framework for residential life cycle cost analysis.

CHAPTER 1. INTRODUCTION

This chapter provides an overview of the research undertaken. The introduction is designed to provide the scope of research, the significance and the definitions that are crucial to understanding the research. It also includes assumptions made, limitations faced, and delimitations set by the researcher.

1.1 Problem Statement

Developers, owners and tenants are reluctant to jump into the investments involved with energy efficient buildings. Newer technologies often have high installation costs, which is one of the major reasons why there is a lack of energy efficient buildings (Ryghaug & Sørensen, 2009). What's overlooked is that buildings are durable structures and long-term investments. Yet, often decision makers and stakeholders look at up-front costs and initial expenses when choosing building systems (Marszal & Heiselberg, 2011).

What stakeholders should be looking at when making decisions about the design and systems of the building is the life cycle cost of those proposed components. Despite the numerous benefits of using life cycle cost analysis, it is not being readily adopted by homeowners and developers in the construction industry. Lack of reliable data, shortage of actual performance measurements, a lack of understanding and uncertainty about potential future savings are some of the reasons (Dwaikat & Ali, 2018; Morrissey & Horne, 2011). Moreover, its adoption in the green building industry, especially for low rise residential buildings, is relatively slow (Ryghaug & Sørensen, 2009). There is need to expand LCCA into the residential sector, where its growth is hampered by inconsistent data and insufficient collaboration between stakeholders (Ramesh et al., 2010).

The purpose of this research is to explore the potential of current LCCA procedures as an evaluation tool for green building strategies by conducting energy usage simulations for different strategies. It will also seek to provide suggestions to improve its adoption for residential buildings.

1.2 Research Questions

1. What energy conservation measures are significant in reducing energy consumption in multi-family residences based on energy simulation data?
2. What is the least life cycle cost for a multi-family residence based on energy simulation data using energy conservation measures identified in this research?

1.3 Scope

This research is a quantitative study aimed to calculate the life cycle costs of a variation of systems in a residential unit. The case study (residence) selected with its existing systems is labelled as “Base Case”. The researcher will compare the base case energy simulation data against variations of the same unit with different green building strategies and finally against a combination of green building strategies that results in the least life cycle cost. Life Cycle Cost Analysis is the tool that has been selected to analyze these different cases.

There are multiple definitions and standards for Green buildings since it is a very broad area of study. For this research work the study will only encompass green building strategies appropriate for a residential unit. Further, the study will focus on features and systems of residential homes that have a sizeable and continual effect on utility bills and related costs.

1.4 Significance

Buildings – both residential and commercial, use 70% of all the electricity produced in the United States (Farhar & Coburn, 2008). Annual Carbon emissions for the generation of electricity used by buildings in the US forms 39% of the country's annual total Carbon emissions (U.S. Department of Energy, 2008). With the advancement in technology, there are numerous solutions available to make buildings greener, for the purposes of this study energy efficiency would be the main goal. Although it is well documented and well recognized that energy efficient buildings are cost effective, there is still a lack of proper understanding of this subject matter.

To make a more economically compelling case for adopting energy efficient strategies the Researcher has used Life Cycle Cost Analysis (LCCA). LCCA, in construction, can be used to compare design alternatives for any building or system considering costs and savings associated with each option over its life (Dwaikat & Ali, 2018a; Snodgrass, 2008). For instance, using LCCA one can determine whether it will be more economically prudent to replace an old mounted air conditioning system with a new one or with a central cooling system. Using LCCA to aid decision-making helps all the stakeholders involved. Homeowners who want to employ energy conservation strategies can gauge the economic effectiveness of their investment. Faced with multiple options, they can make informed decisions that incorporate the life cycle performance of those systems. Moreover, institutions such as USGBC awards Clients who use techniques such as LCCA an extra point in their LEED ratings. In the future USGBC may even require them as part of the accreditation process (Alborzfard, 2012). Contractors can better understand the tradeoff between the added construction cost and lasting benefit to the end user (Hema, 2016). Green building strategies are considered costlier and better understanding of their costs over the life cycle of systems will promote adoption of these strategies.

With the growing public interest in adopting green strategies, there is a lot of scope for future research. This study will also contribute towards any frameworks or decision matrices that shall be formulated by academic researchers for cost-effective and sustainable residential design.

1.5 Assumptions

The following assumptions have been made for the pursuit of this study:

1. Energy use in the building is not influenced by external factors and rare occurrences like power outages or natural disasters.
2. Cost estimates are applicable to the structure at hand and approximately equal to the actual costs borne by the owner.
3. Utility rates considered have not fluctuated during the duration of the study.
4. Number of occupants and overall energy use pattern has not changed during the duration of the study.

1.6 Limitations

The following limitations have been made for the pursuit of this study:

1. Since life cycle cost analysis (LCCA) is an economic tool, tenant comfort is not a parameter considered for the purposes of this study.
2. The life cycle cost analysis (LCCA) study will not address possible trade-offs between economic and aesthetic aspects of the building and systems.
3. LCCA has been used as a tool to account for economic viability and is not an indicator of the level of environmental impact of the selected strategies and their alternatives.

1.7 Delimitations

The following delimitations have been made for the pursuit of this study:

1. The duration of the study will span a full calendar year, covering all seasonal variations and energy use patterns.
2. The weather data file used for eQUEST energy simulation applies to Indianapolis; the closest location with an available weather data file.
3. The life-span of the building is restricted to 50 years.
4. The case has been restricted to a single residential unit.
5. Energy-use pattern and per unit utility prices are reflective of the climatic conditions in Indiana, where the residential unit is located.
6. Features and systems of a building that do not have a sizeable impact on energy consumption have not been considered in the study.

1.8 Definitions

1. Life Cycle Cost Analysis (LCCA): Marszal & Heiselberg (2011) define Life cycle cost (LCC) as an economic method that adopts a structured approach to address all the different costs of the ‘project’ over the given study period with all the potential cost adjusted to reflect the time-value of money.
2. Green buildings: “Green buildings are holistic buildings that in the planning, design and operation have a positive effect on its surroundings” (USGBC).
3. Net Zero Energy Building: “A traditional building which is equipped with sufficiently large renewable energy systems and where the energy production over a year balances out the energy use.” (Marszal & Heiselberg, 2011).

CHAPTER 2. REVIEW OF LITERATURE

This chapter is a summary of the existing research relevant to the researcher's task at hand. A synopsis of the literature has been laid down starting from the consumption of energy by various sectors. Thereafter, energy consumption of residential buildings has been discussed. After having laid down the setting of the problem, research works espousing green building strategies as a solution have been reviewed. A thorough understanding of green buildings- their differing definitions, their types and their challenges has been focused on by the researcher to set the stage for the proposed solution. Addressing the challenges faced in adopting green building strategies, the researcher discusses Life Cycle Cost Analysis (LCCA) as a viable option supported by relevant literature. This chapter ends by stating the gap in research that prompted the researcher to write this current work.

2.1 Background

The U.S is a developed nation and its residents consume a lot of energy to satisfy a plethora of needs. There are five major energy consuming sectors according to the US Energy Information Administration (EIA) – industrial, transportation, residential, commercial and the electric power sector. To put it in terms of the research at hand, the researcher has combined the residential and commercial sectors as the 'buildings' sector and ignored the electric power sector (the power consumed in generating electricity). Then, as published in the EIA's *Monthly Energy Review* (April 2018) the share of energy consumption by end-use sectors in the United States would be as the following figure depicts.

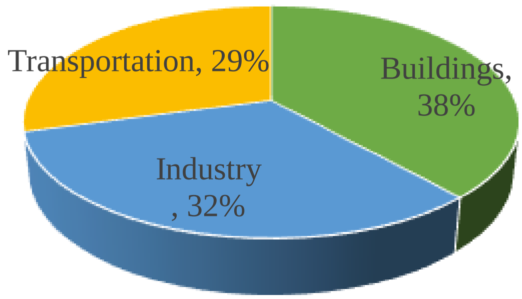


Figure 2.1 Shares of total US energy consumption by end-use sectors in 2017
(Drawn by researcher, adapted from US Energy Information Administration 2017)

It is apparent that the building sector has the highest consumption of energy. This fact is true globally as espoused by Ramesh et al., (2010) in their research where they held buildings alone responsible for 30-40% of all primary energy consumption worldwide as well as 40-50% green-house gas emissions. They follow up that statement with a call for action stating that it is “essential” for the sector to “achieve sustainable development in society”. Hoque (2007), evoked a similar thought by recognizing the growing awareness regarding the need for energy conservation and its reflection in the way we now design buildings.

For new buildings, there is a need to construct in compliance with modern codes that require higher efficiency. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHREA) and Leadership in Energy and Environmental Design (LEED) are two of the most prominent bodies that provide building codes of sustainable construction. The US Department of Energy, The Energy Independence and Security Act of 2007, and The American Institute of Architects call for all new buildings to consume zero net energy by 2030 (Hoque, 2007). With passive design and energy efficient technology, this act seems achievable.

2.2 Residential Energy Consumption

The building sector records the highest energy consumption by end-use sectors (38%) and within it the breakdown of commercial and residential buildings is 18% and 20% respectively. Which essentially implies that households account for almost 55% of total energy consumed by the building sector (EIA, 2017). The EIA further gives a breakdown of the energy consumed in residential units by the different components and systems installed as the following figure shows.

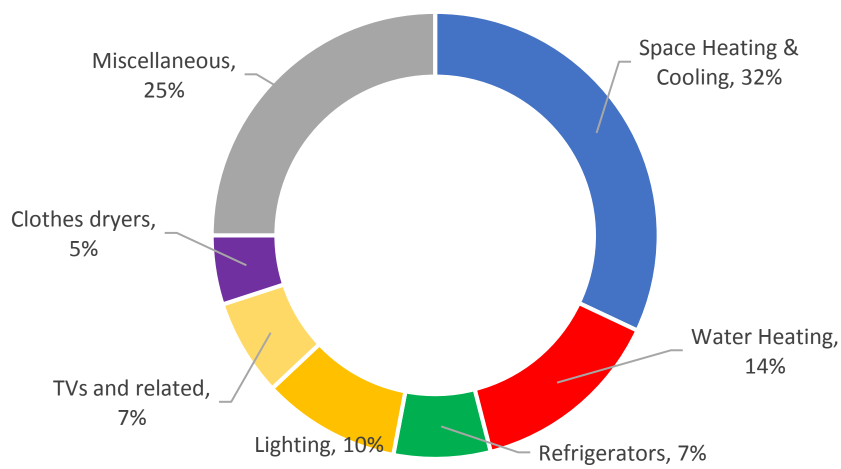


Figure 2.2 Residential Electricity Consumption by End Use in 2015
(Drawn by researcher, adapted from US Energy Information Administration 2017)

The highest electricity consumption in the residential sector is space heating and cooling. In the most recent Residential Energy Consumption Survey (RECS) 2015, conducted by US Energy Information Administration (EIA), it was published that 32% of energy consumption in US homes was for heating and cooling. However, this share of energy consumption, over the years has steadily declined. An explanation for this trend could be the increased use of newer heating systems or better insulation (Kansal & Kadambari, 2010). Even though better heating and cooling systems have been introduced, the total energy consumption has still been on the rise through other electronic appliances (EIA, 2017). Moreover, the fraction of homes in the U.S using air conditioning has continued to increase reaching 87% across the nation in 2015 (EIA, 2015). Even though the equipment used may get more efficient, like in the case of space heating and cooling, the researcher believes that with the current rate of population growth and the introduction of newer systems for increased indoor comfort, the consumption of energy in residentials will stay on the rise. Green buildings and green building strategies should be considered not as alternative design practices but as necessary sustainability measures.

2.3 Green Buildings

The environmental movement is on a rise and add to that the ongoing energy crisis and the concept of green or sustainable buildings is a natural outcome (Kansal & Kadambari, 2010). US Green Building Council (USGBC), the leading authority on green buildings and sustainable construction strategies in the US, defines green buildings as “Holistic buildings, which in the planning, design and operation have a positive effect on their surroundings”. For a more process oriented definition there is Kansal & Kadambari's (2010) research in which they describe a green building as one that “consumes minimum natural resources for its construction and operation throughout its life, in order to conserve the non-renewable resources.” The definition continues with, “It (green building) also emphasizes the reuse recycling and utilization of renewable resources.” and very aptly ends with, “A green building focuses on increasing the *efficiency* of use of the resources”.

According to ASHRAE standard 189.1 (2011) and the National Association of Home Builders’ ICC 700 (2012), green buildings encompass a variety of subject areas:

- Sustainable site
- Energy efficiency
- Water efficiency

- Materials & resources
- Indoor environment
- Emissions

For the purposes of this study, only energy efficiency will be dealt with.

In the following section, certain categories of green buildings have been discussed.

2.3.1 Passive Buildings

Among the many design strategies used in the world for designing green buildings, passive design is the most common and widely used one. A passive building is defined as “A building which is constructed to achieve a comfortable interior climate without a separate active heating device” (Liang et al., 2017).

Passive buildings can achieve low energy requirements through creating a balance between the heat lost and the heat gained (Kang et al., 2015). There are a several elements involved in a passive building design which are detailed below:

1. Building form and orientation:

   Building form includes the interior layout of the house, the floor area, roof types, and the actual geographic location of the residence. Several researchers have emphasized the importance of meticulously selecting the right combination of these factors (Hoque, 2007; Kruzner et al., 2013).

2. Thermal insulation

   Thermal insulation concerns the building envelope; insulation material, thickness, and placement; air leakage; moisture protection; and humidity (Hoque, 2007).

3. Window glazing (Hee et al., 2015)
4. Shades & overhangs

2.3.2 Zero Carbon Buildings

Zero carbon buildings are essentially buildings that balance out their use of fossil fuels by using similar quantities of renewable energy sources. Hence, balancing out their carbon footprint on the planet (Hui, 2010). The terms ‘zero energy’, ‘zero carbon’ or ‘zero emissions’ are used interchangeably to imply buildings that generate their own energy on-site from renewable sources but there is a distinction; zero energy building use renewable sources of energy to satisfy their annual demand and zero carbon buildings can balance out their use of fossil fuels by using as much renewable energy. This research does not consider zero carbon buildings and focuses mainly on the design of zero energy buildings. This is discussed in detail in the section to follow.

2.3.3 Zero Energy Buildings

The idea of energy efficient equipment and design has been around for a long time but more recently the focus has shifted towards making buildings, by design, more energy efficient. In 2006, a team from the National Renewable Energy Laboratory (NREL) and one from the US Department of Energy (DOE) got together and presented at the ACEEE Summer Study Conference in California laying down a formal definition for Net Zero Energy Buildings. Their research, very aptly titled, “Zero Energy Buildings: A critical look at the definition” defines net zero energy buildings as, “… a residential or a commercial building with greatly reduced energy needs through efficiency gains such that the balance of energy needs can be supplied with renewable technologies”(Torcellini, Pless, & Deru, 2006). These buildings have a very high energy performance and rely on renewable energy sources to operate. They produce as much energy as they consume hence, the net zero part (Perlova, Platonova, Gorshkov, & Rakova, 2015). In his work Butera (2013) defines the different aspects of a net zero energy buildings (NZEB) as:

1. **Net zero site energy:** A site NZEB generates as much renewable energy on-site as it uses in a year.
2. **Net-zero source energy**: A source NZEB generates (or purchases) the same amount of renewable energy at its source as it uses annually. Energy at source should include the energy expended in extracting and delivering the energy too.
3. **Net-zero emissions**: This has already been discussed under zero carbon buildings 2.3.2.

Not all research favors net zero energy buildings; Kilkis (2007) argued that net zero energy buildings still impact the environment because they can sometimes create a negative energy balance with the electricity grid. With this thought, NZEBs can be redefined as, "A building, which has a total annual sum of zero energy 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" (Marszal & Heiselberg, 2009).

As discussed in this review of literature, the concept of net zero energy buildings (NZEB) can be complex, thus making it difficult to develop one wholesome definition applicable to all cases (Marszal & Heiselberg, 2009).

2.3.3.1 Design Process of Net Zero Energy Residence

The prevailing design strategies for Green Buildings include a heavily insulated building envelope, high efficiency windows, controlled ventilation, and passive solar considerations (Hoque, 2007). When we look at the construction of a building, it is often realized in a three-step process:

Figure 2.3 Building Construction Process (legacy)

(Drawn by researcher, adapted from Butera 2013)

In his work, Butera (2013) concluded that energy consultants must step in before any construction begins to provide optimum energy & cost-efficient alternatives. This would be the energy analysis stage and would precede Construction. And thus, an improved construction process was proposed:

Figure 2.4 Improved Building Construction Process

(Drawn by researcher, adapted from Butera 2013)

Multiple iterations of the improved process are needed to reach an optimum, energy efficient design. An integrated design process coupled with the latest developments in residential systems can make a building truly net zero energy.

2.3.4 Challenges

Today, only a few net zero energy buildings (NZEB) exist around the world and they show that their design, construction and operation has been challenging for many reasons (Butera, 2013). We can conclude that energy efficiency is still deeply restrained in the construction industry. Some of the major reasons for this are:

1. Lack of public policies to develop energy efficiency strategies (Ryghaug & Sørensen, 2009)
2. Limited or no government efforts in regulating green building and the construction industry (Ryghaug & Sørensen, 2009)

3. A rigid and conservative construction industry (Ryghaug & Sørensen, 2009)
4. Lack of knowledge of new technologies amongst the stalk holders (Shankar Kshirsagar, El-Gafy, & Sami Abdelhamid, 2010)
5. High installation costs (Marszal & Heiselberg, 2011)
6. Lack of consumer (home owner) understanding (Marszal & Heiselberg, 2011)
7. Lack of a quantitative approach to calculate cost benefits of NZE houses (Perlova et al., 2015)
8. Lack of renewable sources of energy based on geographical disadvantages. (Perlova et al., 2015)

2.4 Energy Simulation Tools for Green Buildings

There are a lot of energy simulation software being used by architects and engineers in the early phase of building design to perform energy usage analysis and select between different systems (Zerroug, 2011). Reliability of these software in simulating weather conditions and energy usage combined with a user-friendly interface are major factors that have promoted the use of energy simulation software (Rallapalli, 2010).

Some other benefits are:

1. Making early decisions regarding systems to be used, based on building area and other details. Such software also help you decide on the size of systems
2. Making decisions regarding costs
3. Comparing different design alternatives

Currently there are numerous software simulation tools available. The US Department of Energy maintains a list of over 240 tools on their building energy simulation tool webpage. These software provide a wide array of capabilities from assisting research to aiding commercial energy simulation (Rallapalli, 2010). Han et al. (2014) have identified DOE-2, eQUEST, EnergyPlus, ESP-r, DeST, and Transys as the most widely used building energy simulation software. Of these, EnergyPlus and eQUEST are available free of cost in the United States.

EnergyPlus is a whole building energy simulation tool used to mode the energy performance of a building (Han et al., 2014) . eQUEST is a comprehensive building energy simulation software developed by James J. Hirsch & Associates and Lawrence Berkeley National Laboratory underfunded by the United States Department of Energy (SCE, 2007). eQUEST is an intuitive energy simulation software for all participants in the building design process. Although both software have similar capabilities in whole building energy simulation. Zerroug (2011) has determined that eQUEST produces annual energy consumption results that are more accurate and comparable with actual building consumption. Additionally, Budimir et al. (2013) concluded in their research that eQUEST allows a user to define parametric runs with different system designs and run a comparative analysis with ease. Hence, the researcher has used eQUEST in this research for comparing simulation results between different system designs.

2.5 Life Cycle Cost Analysis (LCCA)

Buildings, in general, are increasingly evaluated to meet norms related to sustainability, cost effectiveness, comfort and safety (Dwaikat & Ali, 2014). However, zero energy buildings are a relatively new concept and face immense adoption challenges as discussed in the previous section. This is where Life Cycle Cost Analysis can help. Life cycle cost analysis (LCCA) is a tool that helps owner and stakeholders investigate the most cost-effective solution. The National Institute of Standards and Technology (NIST) in its 1995 handbook defined life cycle cost as analysis as an economic evaluation tool to help homeowner's and contractor's estimate the cost of owning and operating their building over a period of time (Cabeza, et al., 2014).

Life cycle cost analysis method was first developed by the Department of Defense (DOD) as an analytical method for evaluation of Federal projects (Fernholz, et al., 2013). (Snodgrass, 2008) defines life cycle cost analysis as, "A method of determining the entire cost of a structure, product, or component over its whole life". As life cycle cost includes operation and maintenance costs over a product's lifetime, it is considered a more appropriate evaluation measure when compared to methods that consider only investment costs.

There are different approaches to performing the life cycle cost analysis as detailed below:

Net Savings (NS): For net savings, the key economic benefit looked at is the saving which are defined as the difference between the current worth of the income generated by the investment and the actual amount invested. In this approach the alternative with the highest savings is termed best (Kishk et al., 2003).

Internal Rate of Return (IRR): For the amount invested in a project each year of its life, the percentage earned after deducting all repayments is termed as the internal rate of return. In this approach to LCCA, the alternative with the highest IRR is termed best (Kishk et al., 2003).

Simple Payback: Simple payback is a very simple approach to LCCA. The investment with the shortest pay-back period is termed best (Flanagan et al., 1989).

Net Present Value (NPV): Net present value is a method to calculate life cycle cost (LCC) of a building while factoring in the time value of money. Net present value is calculated by discounting the cash flows, coming in and going out, to the present value (Kishk et al., 2003).

2.5.1 Net Present Value

Net Present Value (NPV) is the most common tool used for life cycle cost analysis (LCCA) (Kishk et al., 2003). However, it is not the most effective method for comparing buildings that have different lifespans (Flanagan et al., 1989). Since this research does not compare different buildings, NPV has been chosen for analysis. The formula developed by Kaufman (1970), is the most widely used method for Life cycle cost calculation.

$$NPV = C + R - S + A + M$$

Where, C is the investment cost, R is the Replacement costs, S is the Resale Value, A is the annually occurring costs and M is the non-annually occurring costs. Another factor used in this calculation is the discount rate. Discount rate is used to calculate the present value of an investment based on the time value of money. It is a representation of the opportunity cost of the investment being made (Dwaikat & Ali, 2018).

This formula has been used for life cycle cost analysis in the LCCA spreadsheet (Appendix B).

2.5.2 Benefits of Life Cycle Cost Analysis

Life cycle cost analysis can serve as a great benchmarking tool for Green buildings, as it quantifies the benefits of green buildings. Hoque (2007) writes, “It is useful for the comparison of different alternatives which satisfy the desired level of performance”. Additionally, it is a great tool to assess the performance of a green building.

The primary advantage LCCA has over other assessment tools is the fact that it allows comparison between different competing strategies for the same project based on the initial cost and the long-term savings that those strategies entail (Ozbay et al., 2003).

For further research, life cycle cost analysis (LCCA) has been researched on as a facilities management tool (Shankar Kshirsagar et al., 2010) and a whole building assessment tool.

2.6 Lack of Research

In a study that examined the use of life cycle costing in the United States that surveyed architects, engineers, and consultants, it was reported that the greatest use of life cycle cost analysis is in Leadership in Energy and Environmental Design (LEED) projects (38%), however the sector with the least applicability of life cycle cost analysis (LCCA) method was residential (7%) (Fernholz et al., 2013). Additionally, Islam et al., (2015) reported that, there is a lack of research in evaluation of residential building design through life cycle costing (LCC) and life cycle analysis (LCA) approaches. Moreover, Morrissey & Horne (2011) identified the gap in research concerning the integration of economic analysis and energy efficiency during the design phase. Research in this field can provide decision makers a quantitative criterion to evaluate zero energy residential buildings.

CHAPTER 3. METHODOLOGY

This chapter details the intent of the research and the methodology used in the study to obtain results. The researcher will first reintroduce the research question and outline a framework followed by detailing the steps undertaken for this research. This chapter also includes details of the case chosen and its significance while outlining the process of data collection and analysis.

3.1 Research Questions

1. What energy conservation measures are significant in reducing energy consumption in multi-family residences based on energy simulation data?
2. What is the least life cycle cost for a multi-family residence based on energy simulation data using energy conservation measures identified in this research?

3.2 Research Framework

Numerous studies in the existing literature have been conducted on zero energy buildings. Additionally, there have been studies on life cycle cost analysis for green buildings. However, there has been a lack of research exploring the application of LCCA in the residential sector. Studies conducted in the realm of green buildings have traditionally been constrained to the commercial sector. This research will use life cycle cost analysis to analyze a residential unit. The analysis will be run on different energy consumption scenarios for a residence and compared with the base energy consumption to identify the combination that results in the least life cycle cost. The framework for this research can be summarized as:

- Identify energy conservation measures for a residence and on-site and off-site energy sources.

- Analyze the various energy consumption and source combinations and simulate the energy use pattern on a suitable software.
- Calculate life cycle cost of each combination and compare.
- Develop cost-benefit analysis for each energy conservation measure based on the above results.

3.3 Justification for use of a Quantitative Case Study

Robert K. Yin (1994) characterized case studies as a tool to be used in scenarios where the researcher exercises little control over the events being studied. Seeing as this research explores the consumption of energy in a residence (event), the researcher has chosen to perform a case study. The energy consumed is being recorded to calculate the overall cost of systems and technologies within the residence using life cycle cost analysis. Life cycle cost analysis is a data intensive tool that needs quantitative information like, in this case, utility bills, and energy simulation data.

3.4 Details of the Case

This case study is based on a multi-family residence located in Indiana. The residence was chosen based on its location, size and energy consumption. Its proximity to the researcher and ease of access throughout the duration of the study makes it ideal. It lies in the US average residential size ranging from 1088 sqft for rental units to 2426 sqft for average house sizes (US Census, 2017). Its energy consumption for the past nine months before this research is also on par with the national average, that is 867kWh per month (U.S. Energy information Administration, 2017).

For life cycle cost analysis, three instances of the same residence will be considered:

Base Case: The base case will involve the systems, technologies, and the energy source as they exist in the residence during the time of this research. Energy consumption data will be collected from utility bills during the period and occupancy details will also be recorded.

Case I: The researcher will select passive design strategies and virtually implement them in a suitable energy simulation software. Data generated therefrom will serve as energy use data for the improved case.

Case II: Using active energy conservation measures the researcher will redesign the residence. Simulation data from the active design case will be used to perform the life cycle cost analysis for this case.

Case III: Employing a combination of passive design and active strategies, the researcher will try to design a net zero energy residence. Life cycle cost analysis will be performed for each alternative to recognize the case with the least life cycle cost.

3.5 Energy Conservation Measures

In section 2.2, the researcher discussed the highest energy consumption areas in a residence by end-use. The highest being space heating and cooling, water heating and lighting (EIA, 2015). In section 2.3.1, passive design was discussed as a green building strategy. Passive design includes building orientation, window glazing, thermal insulation etc. The researcher has selected energy conservation measures, both active and passive, to be used in each case based on their energy saving potential (ASHRAE, 2011). The following table illustrates the Energy Conservation Measures (ECMs) selected for this research and the case in which they'll be used.

Table 3.1 Energy Conservation Measures

Energy Conservation Measures ↓	Case			
	Base Case	Case 1 (passive)	Case 2 (active)	Case 3 (combined)
Passive Measures				
Orientation		✓		✓
Thermal Insulation	✓	✓		✓
Window Glazing	✓	✓		✓
Active Measures				
PV System			✓	✓
HVAC System	✓		✓	✓
Water Heating System	✓			
Lighting Scheme	✓		✓	✓

3.6 Methodology

A detailed step-wise methodology has been summarized below:

Step 1. A review of literature is conducted to analyze the studies conducted in the field of zero energy buildings and life cycle cost analysis for green buildings. Factors impacting green buildings are analyzed and considered for this research.

Step 2. Identify Energy conservation measures (ECMs) for multi-family residences.

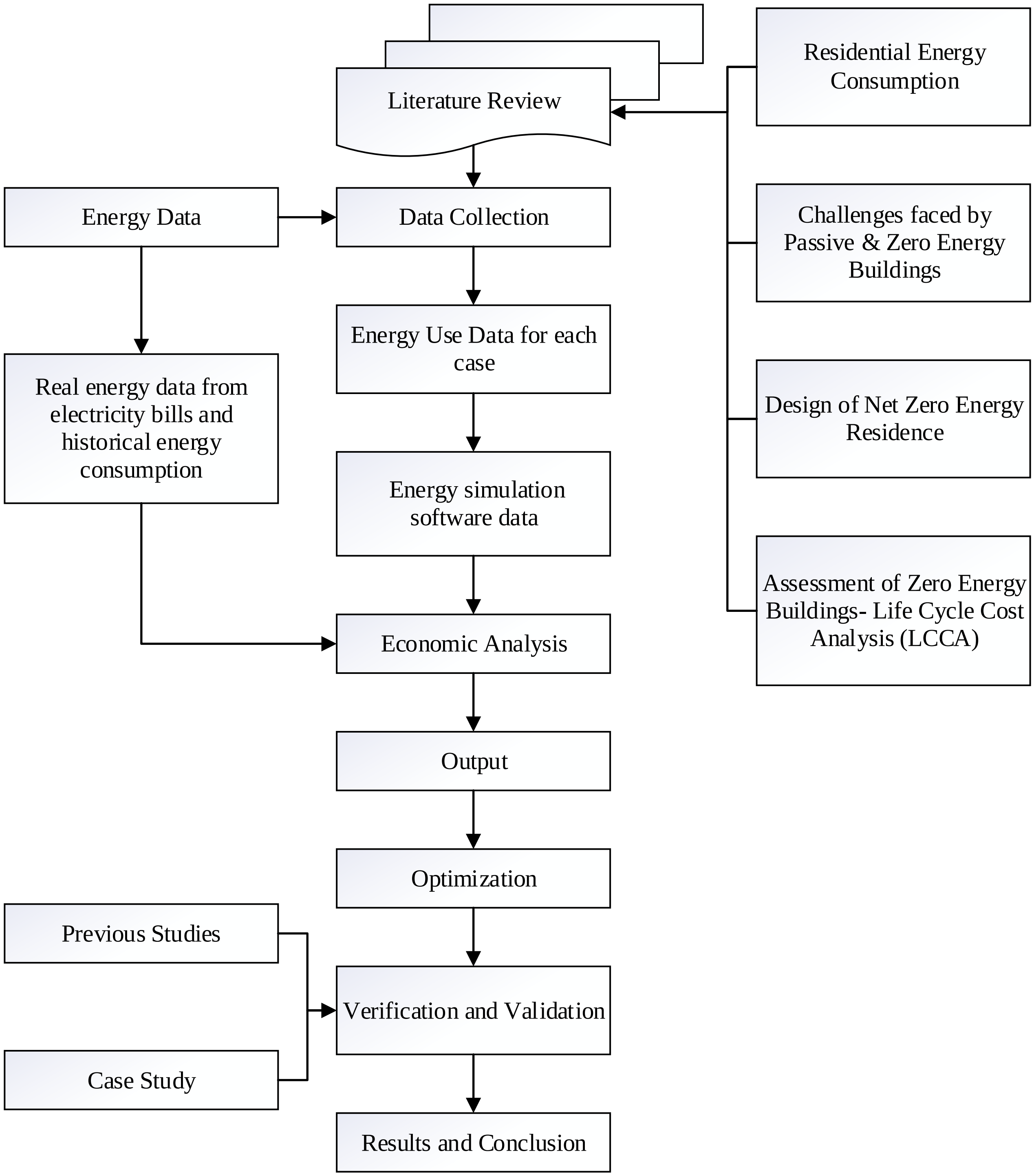


Figure 3.1 Methodology Flow Chart

Step 3. The first stage of the study includes studying a residential unit located in Indiana. Data is collected for this house is in the form of historical energy bills and current system & occupancy data. Data collection is covered in section 3.7.

Step 4. Energy model for the base case is generated on eQUEST. Inputs for energy simulation are based on current available data.

Step 5. The next step is to develop a green building model based on this case study. Energy conservation measures (ECMs) are identified for the residence for three different scenarios:

i. Passive energy conservation measures:
    a. Building orientation
    b. Thermal insulation
    c. Window glazing
ii. Active energy conservation measures
    a. PV system for energy generation
    b. HVAC system
    c. Lighting scheme
iii. Mix of passive design and active ECMs

    This would include ECMs from the previous two models

Step 6. The next step in the research is the cost and energy data calculations. Energy data from eQUEST is used to evaluate operation costs for the house. These costs along with other variables are used to calculate the life cycle cost of the building using net present value method.

Step 7. A comparative economic analysis is carried out between the different scenarios to determine the best option.

Step 8. Verification and validation of the results is carried out by comparing it to previous studies.

Step 9. The results and conclusions of the study are discussed.

3.7 Data Collection

The study aims at evaluating various costs associated with a building. From the literature review, the researcher has identified potential variables involved in this study. These variables are classified into different data sets. The following variables are involved in the study:

1. Occupancy data:
    a. Occupancy profile- Residential
    b. Hours of use
    c. Special data (if any)
2. Physical data:
    a. Area (Sq. ft)
    b. HVAC system details (Capacity, Type, Wattage)
    c. Water heating system details (Capacity, Type, Wattage)
    d. Windows & Glazing (direction, type of glass, single/double paned)
    e. Wall & Insulation details (thickness, material, U-value)
    f. Lighting system details (type, distribution, lumens/sq. ft)
3. Cost data
    a. Construction cost
    b. Monthly costs
        i. Energy bills
        ii. Water bills

iii. Sewage & trash collection bills

c. Maintenance costs

d. Cleaning costs

e. Inflation

f. Other related costs

4. Maintenance details

a. Maintenance cycle

b. Cleaning cycle

The sources of this data are divided into the following categories:

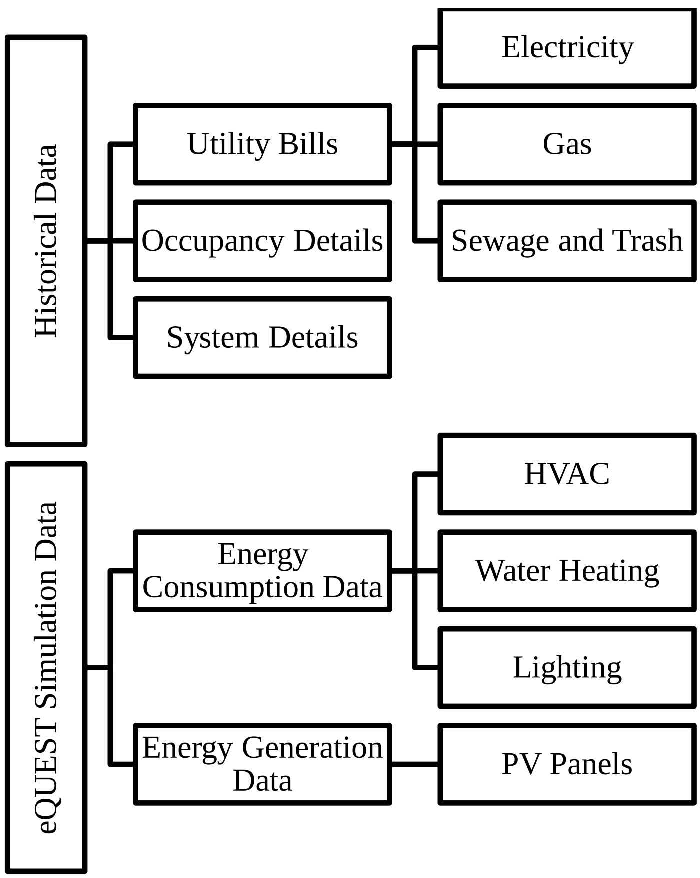


Figure 3.2 Data Sources

These variables will be studied by the researcher for the existing house. The detailed inputs for energy simulation software and life cycle cost analysis have been discussed in the following chapter.

3.8 LCCA Model

As mentioned in literature review, LCCA methodology used for this study is through Net Present value (NPV). An LCCA spreadsheet developed by Cal State University has been used for this research. The full sheet has been presented in the Appendix and the results of the of the analysis have been discussed in chapter 5.

3.9 Summary

The methodology chapter has laid down the research framework, the research design, the elements of this case study and the step-wise methodology that will be followed in this study. The data collection procedures and the variables in this study have also been outlined. Consequently, the next chapter will show the data collected and the analysis performed.

CHAPTER 4. MODEL BUILDING AND SIMULATION

This chapter outlines the digital building model, features of the simulation software (eQUEST) and inputs to the simulation software. The inputs have been categorized first as general inputs to eQUEST and then by the cases being compared in the previous chapter. These results from eQUEST have been used to develop life cycle cost analysis models for this research.

4.1 eQUEST Simulation Overview

eQUEST simulates energy consumption for multi-family housing for the whole building. For the purposes of this research, the eQUEST model has been designed such that it performs simulation for only a part of the building. The inputs have been categorized into two section – constants and variables. Constant inputs are those that have not been changed in any of the cases and variable inputs are those that have. Sections 4.2 and 4.3 summarize the inputs to the eQUEST simulation model.

4.2 Model Inputs - Constants

The location of the building, weather data, plug loads, roof insulation and other parameters have not been changed in any of the cases. The aim of this research is to identify systems that have a *significant* impact on energy consumption and the researcher has deemed the following inputs as constants throughout all simulations.

4.2.1 Site and Weather

The case being studied is part of a multi-family low-rise building located in West Lafayette, Indiana occupying an area of 1000 sq. ft. It is a 4-bed 2 bath apartment with 4 occupants. It is located on the second floor of a four-story building. The layout of the research location is shown in the figure below:

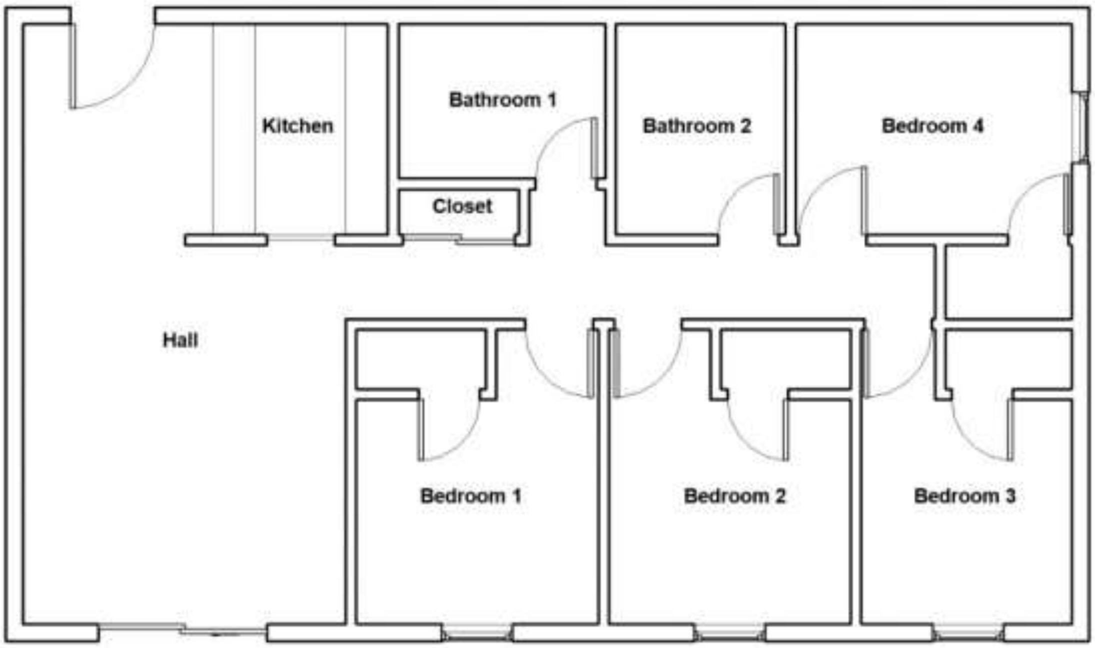


Figure 4.1 Floor Plan of the research location

The weather data file (.bin extension) used is of the Indianapolis region.

4.2.2 Apartment Location

An external shell for the building has been defined in eQUEST as shown in the figure below:

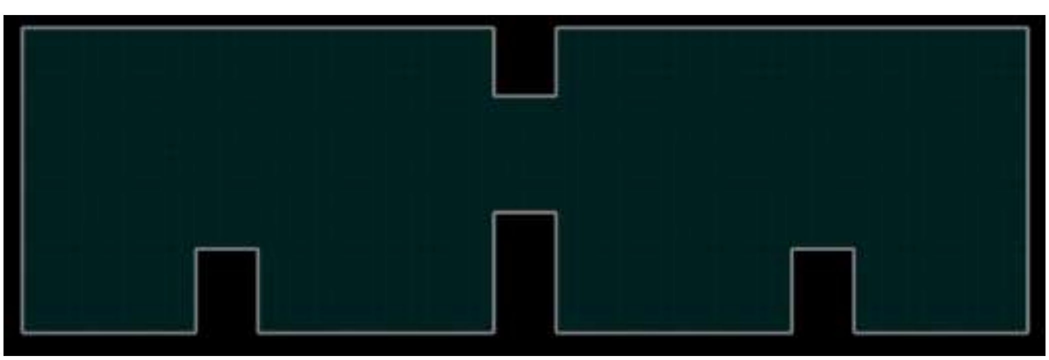


Figure 4.2 Building Shell in eQUEST

The apartment has one floor below grade and one floor above grade to account for accurate thermal insulation and the amount of daylight received.

4.2.3 Equipment Load

Equipment load has been given as 0.5 kWh/Sq. ft. and all energy consuming systems in the building other than the ones in the research location have been set to zero.

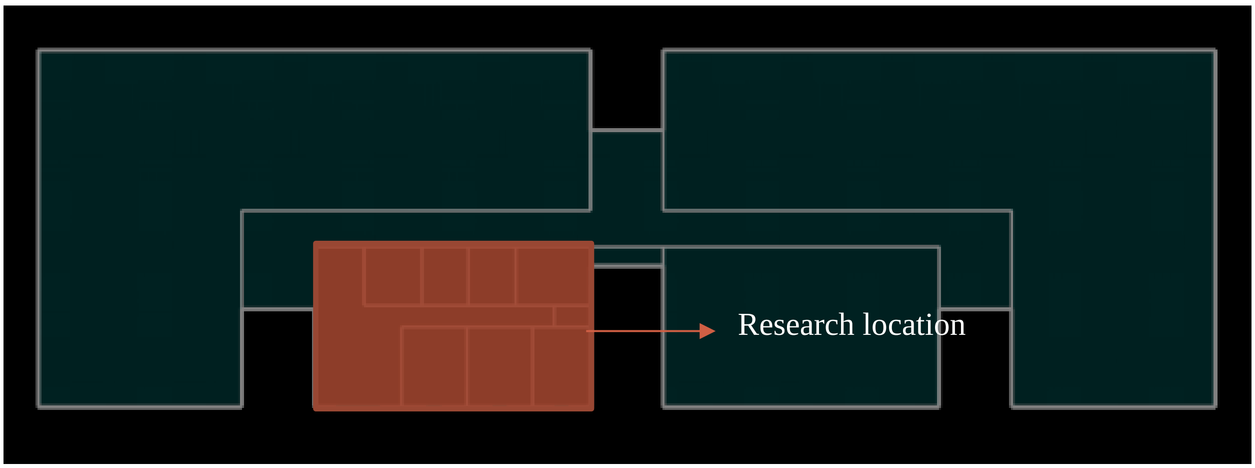


Figure 4.3 Research location in the building

4.2.4 Temperature Set Points

Table 4.1 HVAC Temperature Set Points

Cooling Set point	68 ^{o}F
Heating Set Point	75 ^{o}F

The occupants turn on the system when the internal air temperature goes above 68 ^{o}F during summers and below 76 ^{o}F during winters. Since, set points are a parameter that change according to occupant comfort, the researcher has not changed these in any of the simulations.

4.3 Model Inputs – Variables

4.3.1 Building Orientation

The building's long axis is NS axis with the windows facing east. The figure below shows the orientation of the building. There is no vegetation on the east side of the building. There is one opening on the west side and two exterior openings on the east side.

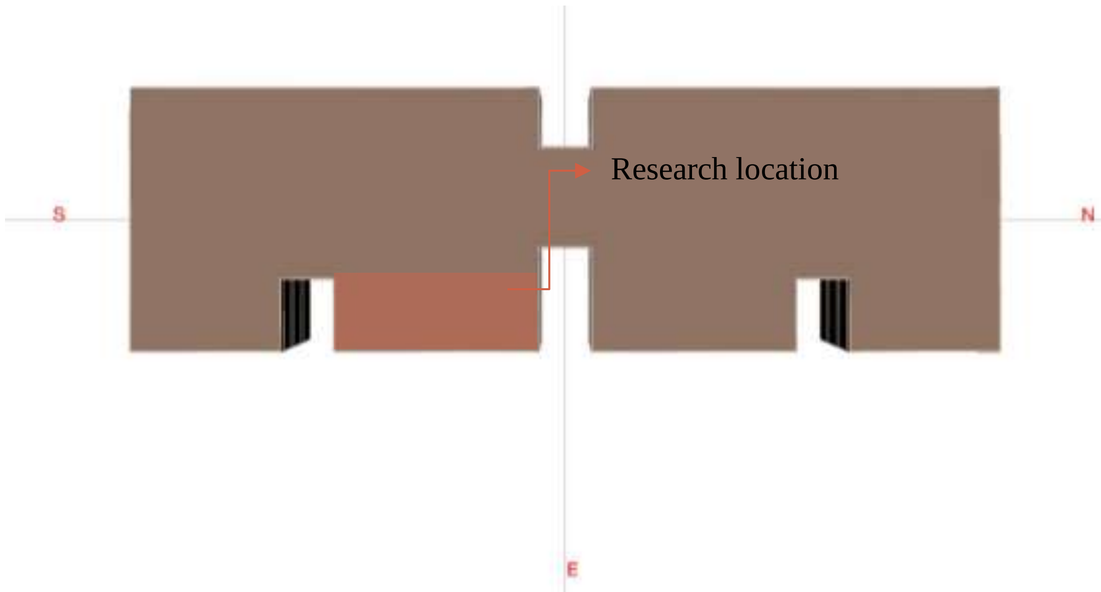


Figure 4.4 Building Orientation

4.3.2 Thermal Insulation

eQUEST has preset values for 8" exterior walls. The researcher has collected the U-values of the exterior wall assembly from the building management and corroborated it with the default value from eQUEST. The following inputs are required for this simulation:

Table 4.2 U values of Envelope features

Envelope Feature	**U-Value**
Exterior Wall (Wood siding on wooden stud; foam insulation)	Mass U-value: **0.103** BTU/ ^{o}F ft^{2} hr
Roof Insulation	n/a

Since the research location is one grade above ground and 2 floors above the apartment, roof insulation is not required for this simulation.

4.3.3 Window Glazing

As mentioned earlier in 4.2.1, the windows of the apartment face east. The location of the glazing is as follows:

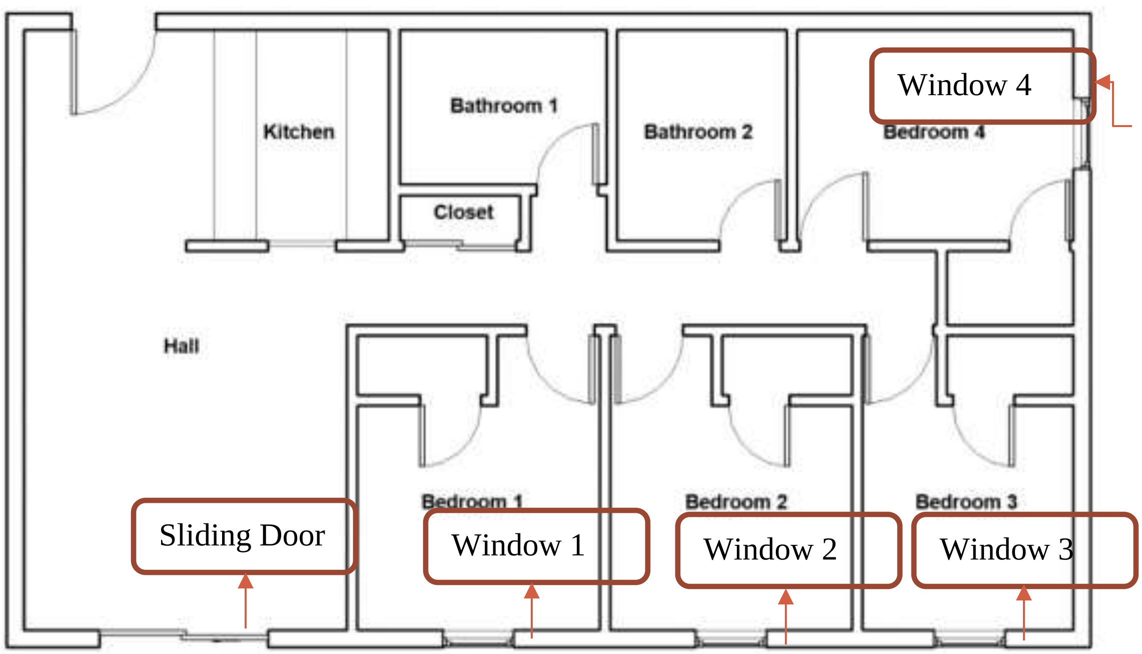


Figure 4.5 Location of Glazing

The thermal properties and details of the glazing are summarized in the table below:

Table 4.3 Glazing Properties

Glazing	U-value	Shading Coefficient	Surface Area
Sliding Door (Non-tinted glass, aluminum frame)	0.35 BTU/ ^{o}F ft^2 hr	0.36	39 ft^2
Windows (single hung, non-tinted glass in an aluminum frame with grill on)	0.35 BTU/ ^{o}F ft^2 hr	0.36	14.5 ft^2 x 4 nos.

4.3.4 HVAC System

The HVAC system is a packaged air-conditioning unit manufactured by Rheem, model No. reab1010bbs. The conditioned and non-conditioned spaces in the apartment are visualized in the figure below:

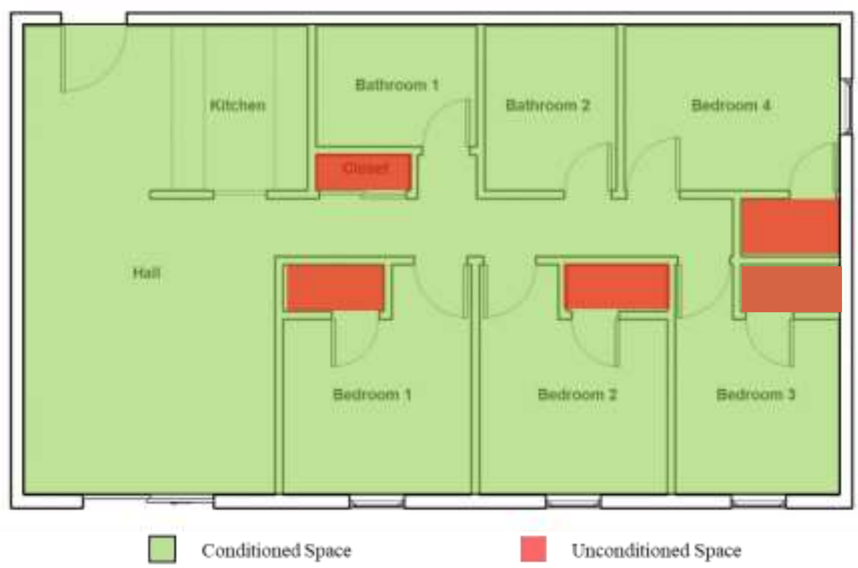


Figure 4.6 Conditioned & unconditioned Spaces

For the purpose of this simulation, conditioned spaces are defined as the spaces having air vents. HVAC parameters as obtained from the manufactured unit present in the apartment have been tabulated below:

Table 4.4 HVAC System and Usage Details

HVAC Parameters	**Value**
Energy Efficiency Ratio	8.5
Cooling Set point	68 ^{o}F
Heating Set Point	75 ^{o}F

During summer months, the cooling in HVAC system is turned off when it reaches the cooling set point. While in winter months, the system keeps running non-stop with the occupants making minor adjustments to the heating set point for comfort.

Within the eQUEST simulation the heating and cooling runs non-stop even when the interior temperature reaches the set point both in summer and winter months. The system usage also depends on the e air temperature.

4.3.5 Lighting

The current residence uses a combination of LED and incandescent lighting fixtures. The below table summarizes the placement and details of the lighting fixtures throughout the house.

Table 4.5 Lighting fixture distribution

Area	LEDs	Incandescent	Lighting Power Density (W/sq. ft.)
Hall	2	3	0.624
Kitchen	0	2	1.562
Bedroom 1	0	2	1.01
Bedroom 2	2	0	0.283
Bedroom 3	0	2	1.136
Bedroom 4	0	2	1.209
Toilet 1	2	0	0.549
Toilet 2	0	2	1.961
Average LPD			**0.895**

Lighting usage is affected by occupancy of spaces and the researcher has split the space into three different zones based on their peak occupancy hours as summarized in the figure below:

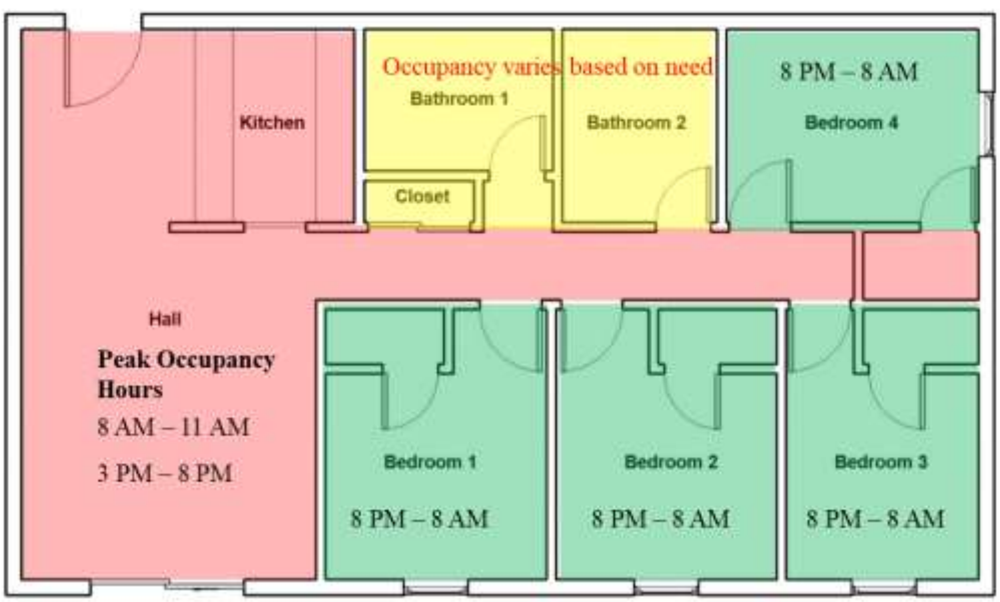


Figure 4.7 Peak occupancy hours for lighting usage

Based on the researcher's observations, the hall and kitchen have highest occupancy during the day and evening. This is the time when occupants prepare food and have meals. In their individual rooms, highest occupancy is during nighttime, that is, from 8pm to 8am. Overall in the house, occupants turn off lights at about 11:30pm and turn them on at about 8am.

eQUEST requires both occupancy details and lighting schedules.

4.4 Photovoltaic Systems

Currently, eQUEST lacks the ability to simulate PV systems and incorporate their energy savings as the researcher would like to do in Case 2 and Case 3. So, the researcher has used the National Renewable Energy Laboratory's (NREL) PVWatts® Calculator to develop an estimate of the energy savings potential of PV systems for this location and residence.

The inputs to the PVWatts® calculator are summarized in the table below:

Table 4.6 Inputs to PVWatts® Calculator

Inputs	Value
Location	West Lafayette, IN
Area Available	28 m^2 (Building roof area)
Average Electricity Rate	0.103 $/kWh
Annual Energy Consumption	18,011 kWh

The PVWatss® Calculator will, for the above inputs, provide the PV system specifications that are appropriate in this case and the potential energy production that can be expected from such a system. This data has been used by the researcher to calculate net energy consumption under Case 2 and Case 3.

4.5 Building Model – Case Data

All the data mentioned above will fall under the “Base Case” simulation and will be used to simulate the existing performance of the building. The three cases that the researcher aims to study have been discussed in the previous chapter. This subsection outlines the data for those cases.

For Case 1, which is a passive energy conserving model, the researcher has changed the Azimuth input to eQUEST in order to change building orientation so that it receives more natural sunlight. Exterior envelope value has also been changed for higher efficiency with the aim to reduce heating and cooling loads.

For Case 2, the researcher has changed values for active systems used in the base case. HVAC system and lighting scheme have more energy efficient alternatives in eQUEST. To offset other sources of energy consumption, the researcher has added a PV system.

Case 3 is a combination of active and passive energy conservation measures. Inputs from Case 1 and Case 2 have been used.

The table below summarizes the data for the three cases:

Table 4.7 Inputs to eQUEST for all Cases

EEM	Base Case	Case 1	Case 2	Case 3
Building Orientation				
Azimuth	270°	180°	270°	180°
Thermal Insulation				
Exterior Wall U-Value (BTU/ °F ft² hr)	0.103	0.044	0.103	0.044
Glazing				
U Value (BTU/ °F ft² hr)	0.35	0.27	0.35	0.27
Shading Coefficient	0.36	0.22	0.36	0.22
HVAC				
EER	9	9	13.5	13.5
Lighting				
Average LPD (W/Sq. ft.)	0.895	0.895	0.325	0.325
Photovoltaic System				
Available Roof Area	-	-	28 m^2	28 m^2

These 3 cases were compared to the Base Case and a comparative analysis has been developed.

4.6 Summary

The values presented in this chapter have been used as inputs to the eQUEST simulation model. The results obtained from eQUEST, the PVWatts® Calculator, and Life Cycle Cost Analysis are discussed in the following chapter.

CHAPTER 5. ANALYSIS AND RESULTS

The previous chapter outlined the existing data of the research location, the inputs to the simulation software and highlighted the difference between the cases. This chapter presents the results obtained from the energy simulations and discusses a comparative analysis between the simulation results of the different cases. The chapter is organized as per the two research questions. The first part answers the question about what energy conservation measures are significant by presenting the findings of the energy simulations in the four cases. The second part includes the Life Cycle Cost Analysis for each case; the numbers that serve as input to this analysis and the results obtained from it.

5.1 Energy Simulation Results

5.1.1 Base Case Simulation Results

The base case is the simulation result for the existing case study. Energy Simulation was run for the following inputs:

Table 5.1 Base Case inputs for simulation

Parameter	**Base Case**
Building Orientation	
Azimuth	270°
Thermal Insulation	
Exterior Wall U-Value (BTU/ °F ft^2 hr)	0.103
Glazing	
U Value (BTU/ °F ft^2 hr)	0.35
Shading Coefficient	0.36
HVAC	
EER	9
Lighting	
Average LPD (W/Sq. ft.)	0.895
Photovoltaic System	
Available Roof Area	--

The annual energy consumption by system for the existing conditions of the building is as follows:

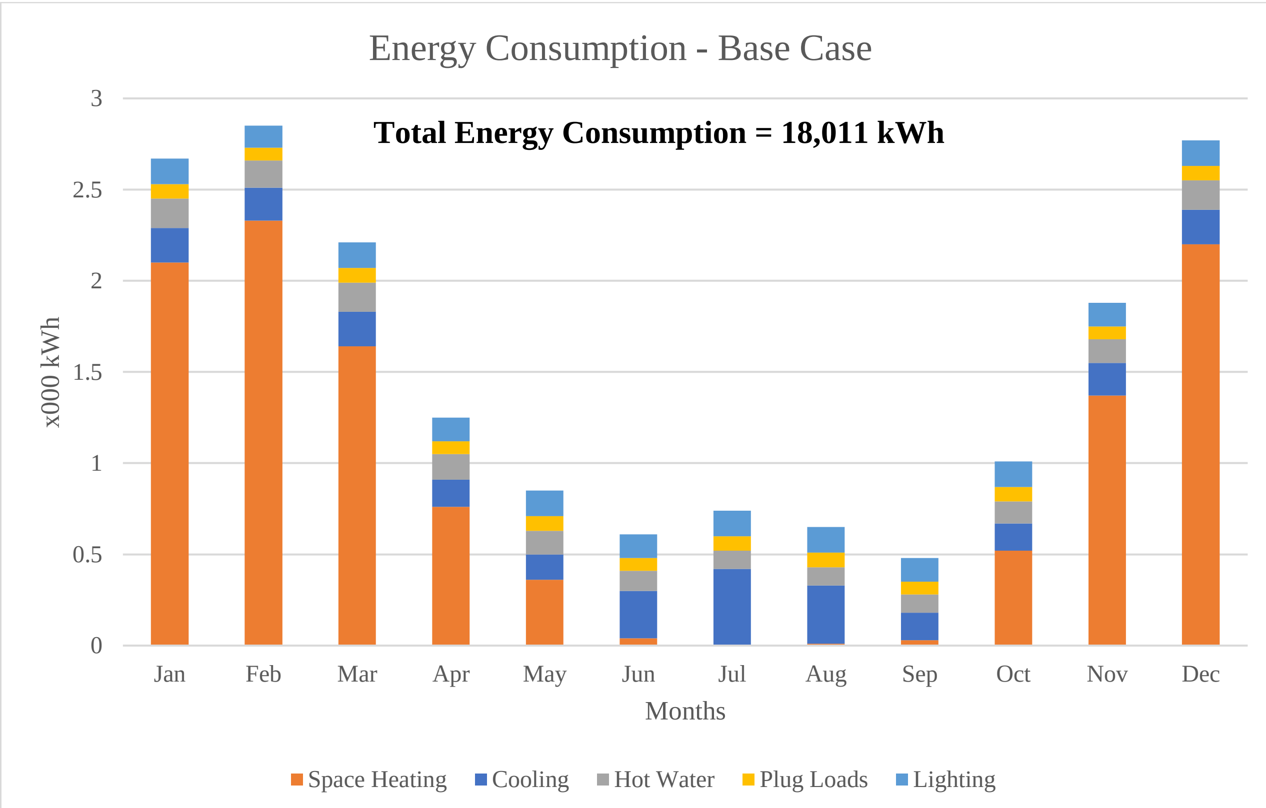


Figure 5.1 Energy consumption breakup by end use for Base Case

The total energy consumed for one year was 18,011 kWh. The consumption of electricity varied over the year, with the highest consumption seen during winters due to space heating requirements. eQUEST runs HVAC at the heating set point till the interior temperature is equivalent to the exterior air temperature, which during wither months is extremely rare, hence the high HVAC usage. Water heating and lighting has remained almost constant throughout the year because lighting density load remains constant through the year. Additionally, since the number of occupants remains same, water heating demands remain almost the same.

5.1.2 Energy Simulation Validation

The Base Case energy simulation model was validated against the actual utility bills accrued by the researcher over the past year. The following table lists the actual energy consumption for 2018 against the annual consumption simulation in eQUEST

Table 5.2 Actual vs Simulated annual energy consumption

Month	**Energy (kWh)**	
	Actuals	Simulation
January	2213	2680
February	2345	2850
March	1670	2200
April	1450	1270
May	1001	840
June	951	620
July	867	740
August	1109	650
September	1277	500
October	1105	1010
November	1709	1890
December	2125	2770

The chart below shows this comparison:

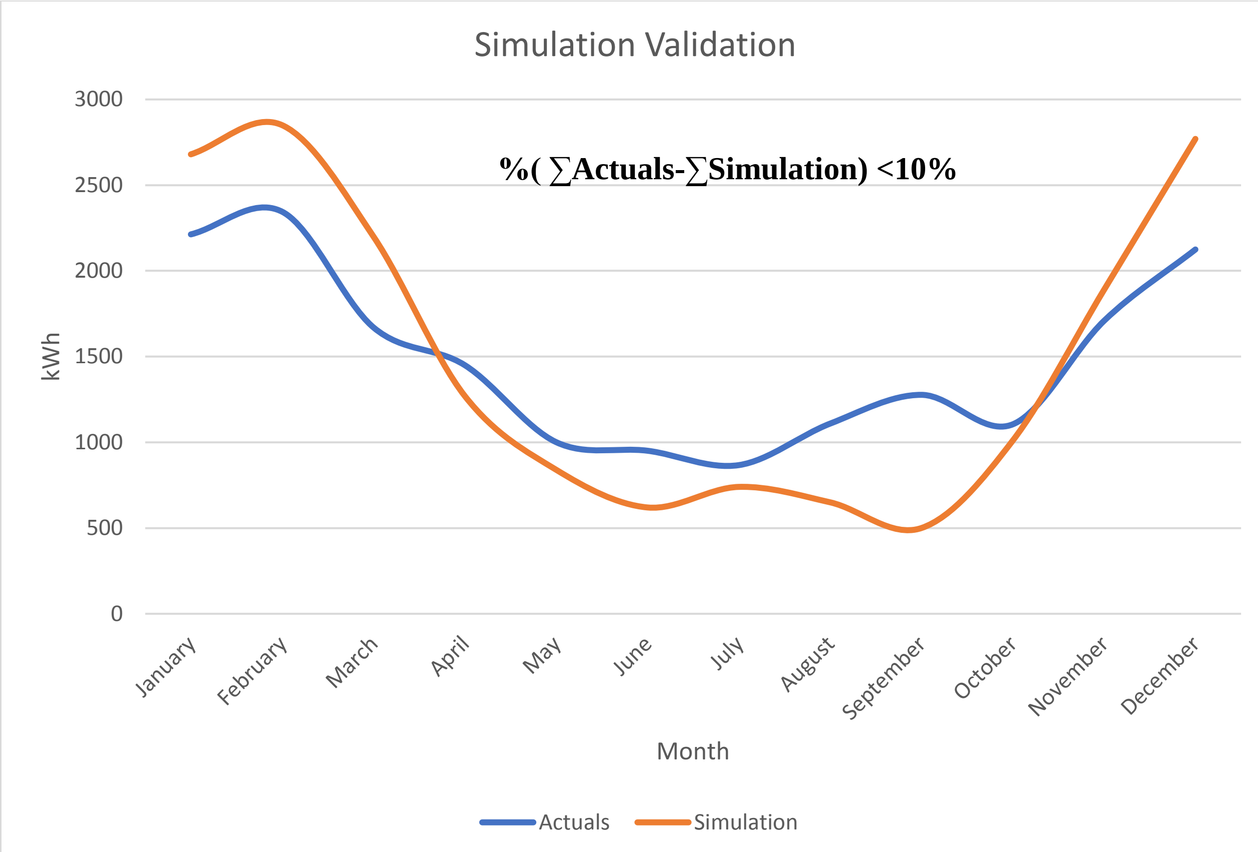


Figure 5.2 Validation of Simulation Model

The overall energy consumption in both cases is close with seasonal variations. The researcher has used the difference between the annual energy consumption between the model and actuals to justify the similarity.

A few factors influencing the seasonal variation in results can be attributed to the following:

1. Due to a software limitation weather data file used in the energy model is from Indianapolis, while the actual location is West Lafayette. Even with the proximity, there are seasonal variations in the temperature which results in a difference in energy consumption.

2. The software cannot predict occupant behavior, which plays a huge role in energy consumption. Although heating & cooling set points have been defined by the researches, the occupants do change heating and cooling based on comfort needs
3. eQUEST has set parameters & predefined values which have been approximated as close to the actual conditions as possible by the researcher, yet it leaves room for some variations

Based on the similarity between the actual energy consumption and the simulation, the researcher has established the validity of the simulation model.

After having established the validity of the model, the same model is used for the remaining cases with parametric runs for the changing variables.

5.1.3 Parametric Runs

5.1.3.1 Case 1

As discussed in the previous section, the researcher aims to establish energy conservation through passive design strategies for Case 1. The parameters have been changed and their results have been analyzed below:

Parameters Changed

1. Azimuth
2. Thermal Insulation of Exterior Walls
3. Glazing

Table 5.3 Case 1 inputs for simulation

EEM	Base Case	Case 1
Building Orientation		
Azimuth	270^{o}	180^{o}
Thermal Insulation		
Exterior Wall U-Value (BTU/ ^{o}F ft^{2}hr)	0.103	0.044
Glazing		
U Value (BTU/ ^{o}F ft^{2}hr)	0.35	0.27
Shading Coefficient	0.36	0.22
HVAC		
EER	9	9
Lighting		
Average LPD (W/Sq. ft.)	0.895	0.895

Results

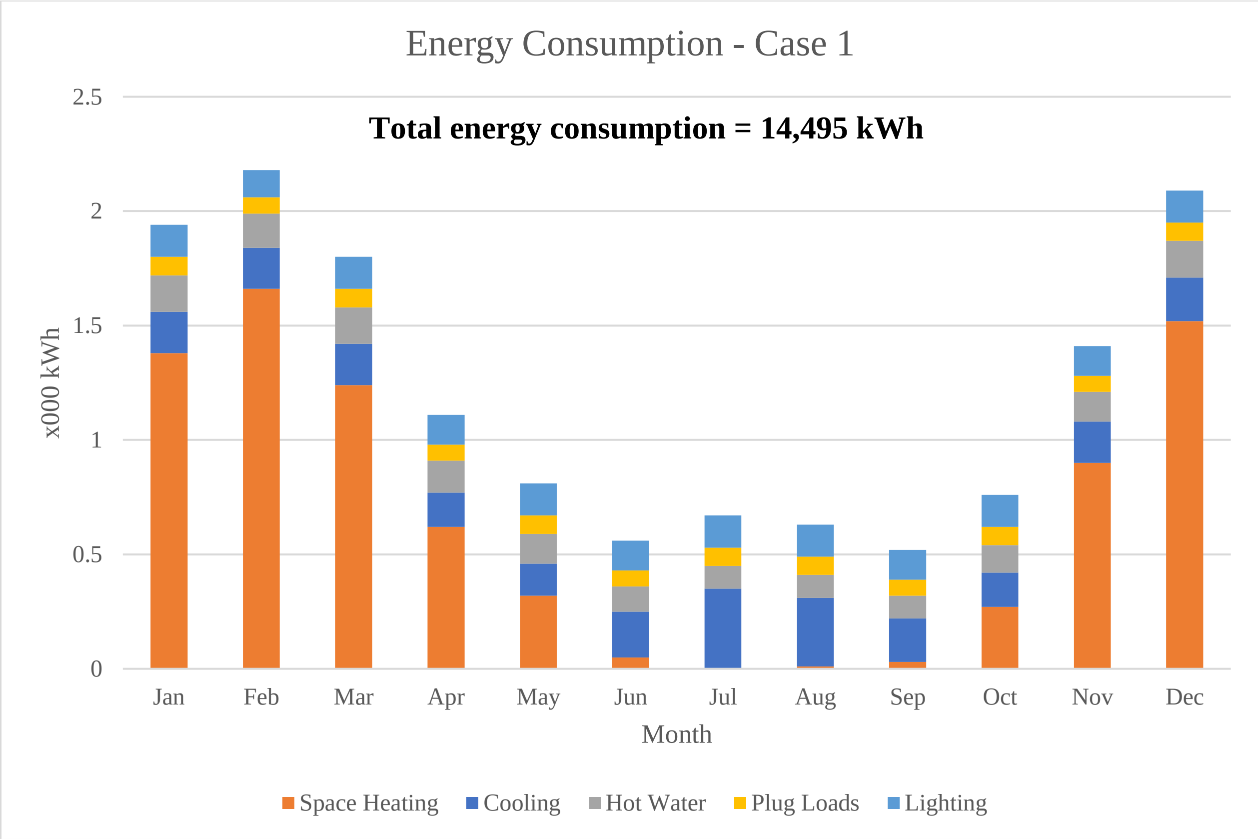


Figure 5.3 Energy consumption breakup by end use for Case 1

With the change in building envelope, the researcher aimed for lower heating and cooling needs which can be seen here. The difference in energy consumption from base case has been tabulated below

Table 5.4 Percentage difference in annual energy consumption – Case 1 and Base Case

System	**Base Case**	**Case 1**	**% diff from Base Case**
Space Heating	11.36	8.00	-29.58%
Cooling	2.52	2.39	-5.16%
Hot Water	1.56	1.56	0.00%
Plug Loads	0.91	0.91	0.00%
Lighting	1.62	1.62	0.00%
Total	**17.97**	**14.48**	**-19.42%**

With a 25% reduction in space heating & cooling, it can clearly be seen see that passive energy conservation measures do play a significant role in reducing energy consumption in a building.

5.1.3.2 Case 2

For Case 2 the researcher the researcher has added some energy conservation measures and changed some existing energy conservation measures to tackle high heating and cooling loads. LED lighting has been used throughout the building replacing all incandescent lighting. Additionally, a PV system has been added to calculate the energy generating potential for the apartment. The parameters changed in this Case and the results have been analyzed below:

Parameters Changed

1. HVAC System
2. Lighting Fixtures
3. PV System

Table 5.5 Case 2 inputs for simulation

EEM	Base Case	Case 2
Building Orientation		
Azimuth	270°	270°
Thermal Insulation		
Exterior Wall U-Value (BTU/°F ft^2 hr)	0.103	0.103
Glazing		
U Value (BTU/°F ft^2 hr)	0.35	0.35
Shading Coefficient	0.36	0.36
HVAC		
EER	9	13.5
Lighting		
Average LPD (W/Sq. ft.)	0.895	0.325
Photovoltaic System		
Available Roof Area	-	28 m^2

Results From eQUEST

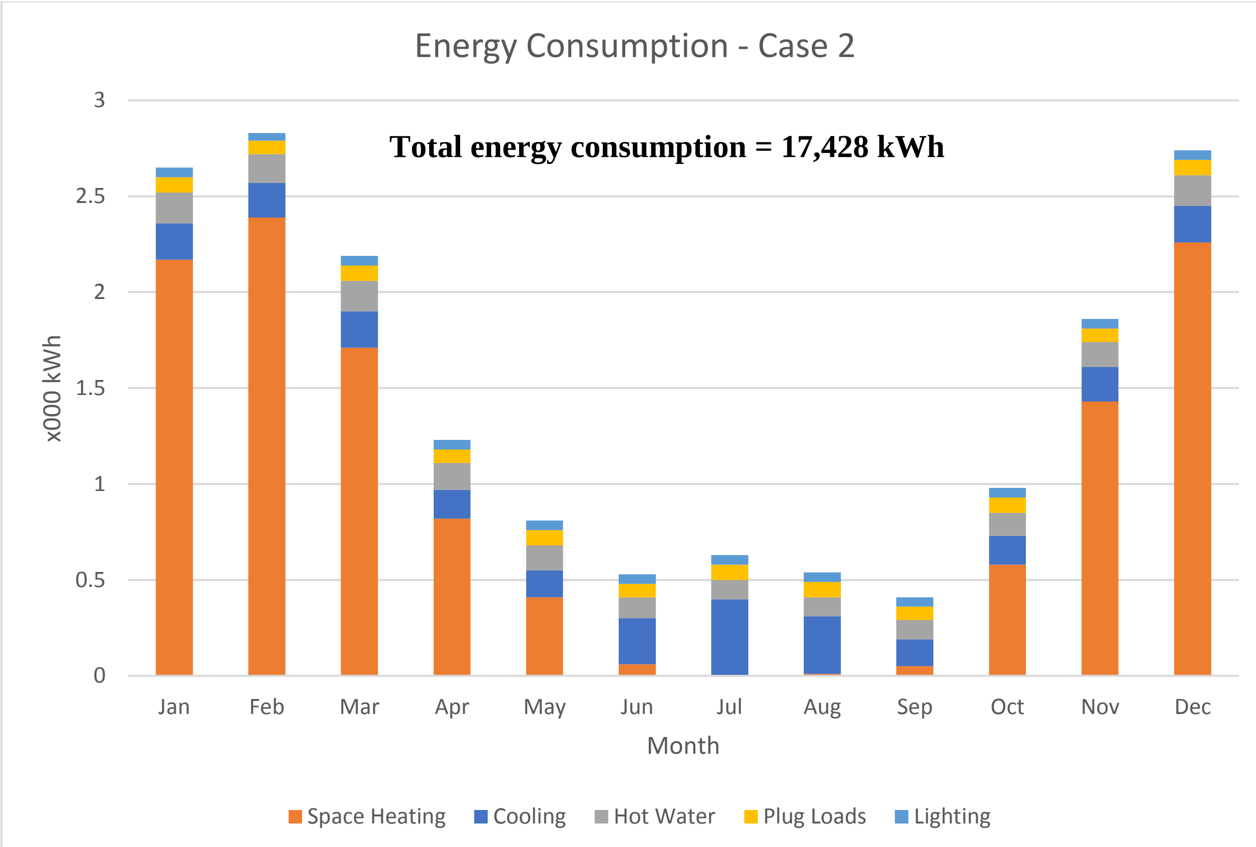


Figure 5.4 Energy consumption breakup by end use for Case 2

Total energy consumption in Case 2 came out to be 17,428 kWh.

Results from PVWatts® Calculator

Based on the inputs outlined in section 4.3 of the previous chapter, the PVWatts® Calculator gives the following results:

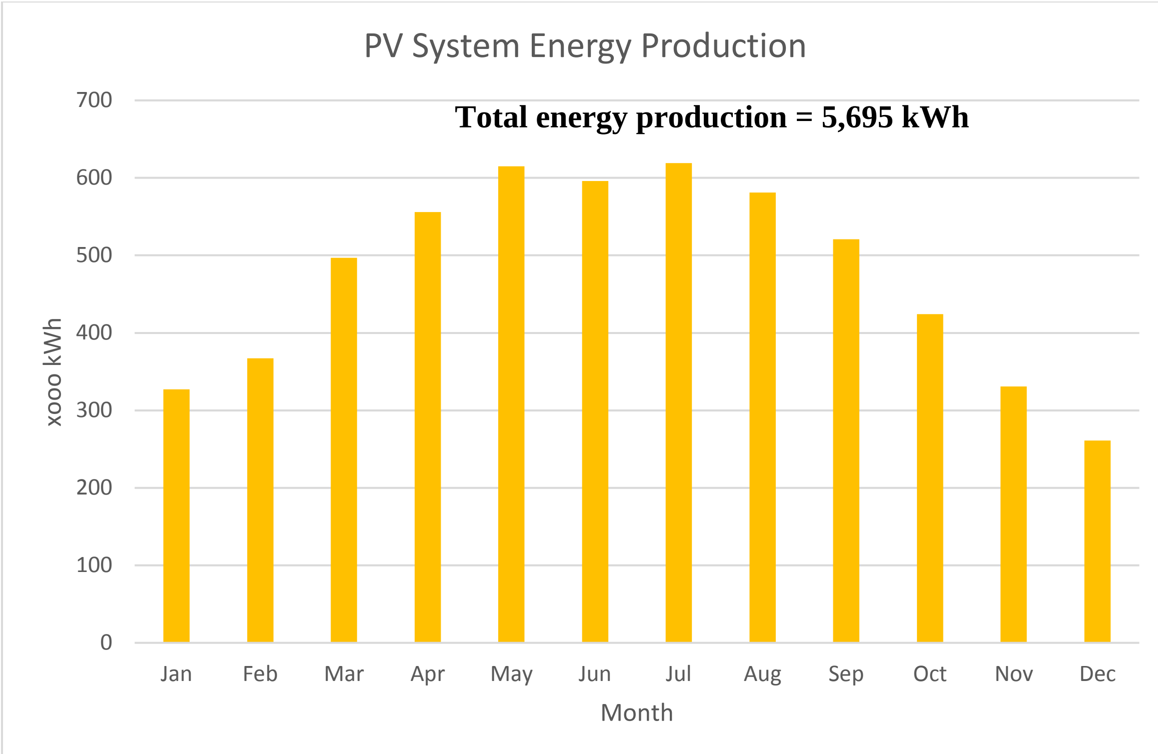


Figure 5.5 Annual energy production from PV system

Net Energy Consumed

Energy consumed according to eQUEST simulation: 17,428 kWh

Energy saved according to PVWatts® = 5,695 kWh

Net energy consumed = 11,733 kWh

Table 5.6 Percentage difference in annual energy consumption – Case 2 and Base Case

System	Base Case	Case 2	% diff fromBase Case
Space Heating	11.36	11.89	4.67%
Cooling	2.52	2.45	-2.78%
Hot Water	1.56	1.56	0.00%
Plug Loads	0.91	0.91	0.00%
Lighting	1.62	0.59	-63.58%
Total	**17.97**	**17.4**	**-3.17%**
PV	0	-5.695	
Total after PV	**17.97**	**11.705**	**-34.86%**

With the addition of a PV system, the energy consumption for Case 2 has gone down to 11,733 kWh. When comparing with Base Case, there is a 3% increase in heating and cooling loads even with the use an HVAC system with a higher Energy Efficiency Ratio (EER). Comparing this to Case 1, HVAC consumption has increased by 37.9% suggesting that passive measures in case of heating and cooling are more influential in reducing energy consumption than active systems. Additionally, lighting energy consumption has reduced by 63% when compared to the Base Case

5.1.3.3 Case 3

The researcher has used parameters from Case 1 and Case 2 to design an energy efficient residential unit. The parameters changed in this model and the results obtained have been analyzed below:

Parameters Changed

1. Azimuth
2. Thermal Installation
3. Glazing
4. HVAC System
5. Lighting Fixtures
6. PV System

Table 5.7 Case 3 inputs for simulation

EEM	**Base Case**	**Case 3**
Building Orientation		
Azimuth	270°	180°
Thermal Insulation		
Exterior Wall U-Value (BTU/ °F ft^2 hr)	0.103	0.044
Glazing		
U Value (BTU/°F ft^2 hr)	0.35	0.27
Shading Coefficient	0.36	0.22
HVAC		
EER	9	13.5
Lighting		
Average LPD (W/Sq. ft.)	0.895	0.325
Photovoltaic System		
Available Roof Area	-	28 m^2

Results from eQUEST

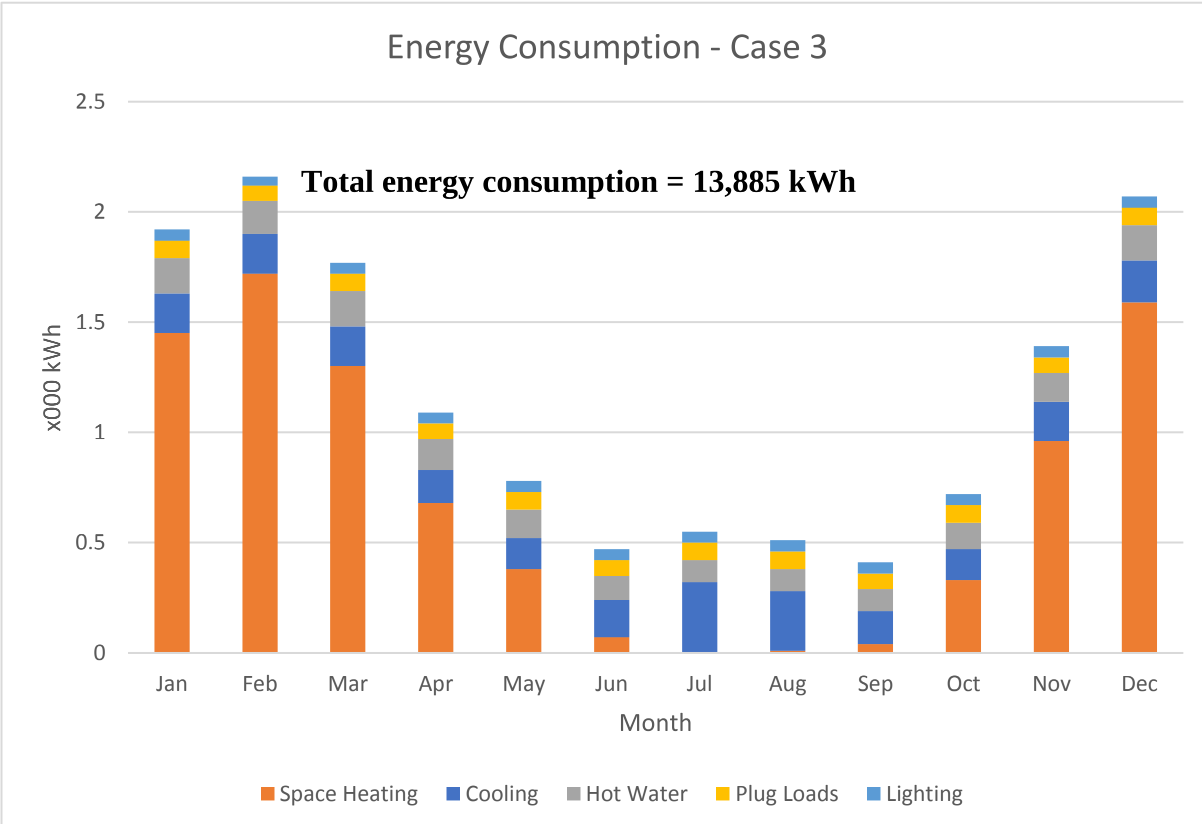


Figure 5.6 Energy consumption breakup by end use for Case 3

Results from PVWatts® Calculator

Same as Case 2 where the proposed PV system produced 5,695 kWh annually.

Net Energy Consumed

Energy consumed according to eQUEST simulation: 13,885 kWh

Energy saved according to PVWatts® = 5,695 kWh

Net energy consumed = 8,190 kWh

Table 5.8 Percentage difference in annual energy consumption – Case 3 and Base Case

System	Base Case	Case 3	% diff fromBase Case
Space Heating	11.36	8.53	-24.91%
Cooling	2.52	2.25	-10.71%
Hot Water	1.56	1.56	0.00%
Plug Loads	0.91	0.91	0.00%
Lighting	1.62	0.59	-63.58%
Total	**17.97**	**13.84**	**-22.98%**
PV	0	-5.695	
Total after PV	**17.97**	**8.145**	**-54.67%**

With the addition of a PV system to the energy simulation results, net consumed energy stands at 8,190 kWh. Annual heating and cooling load has reduced to 1,078 kWh, which is 22.5% lower than the Base Case but still 3.5% higher than Case 1 confirming that passive design measures such as an efficient building envelope provides better results than using high EER systems. Energy consumption through lighting remains same in Case 3 and Case 2, which is 63% lower than Base Case. The PV system generates 5,695 kWh of energy annually. This alone accounts for 31% reduction in energy when compared to the Base Case.

5.1.4 Comparative Analysis

Total Annual Energy Consumption – by Case

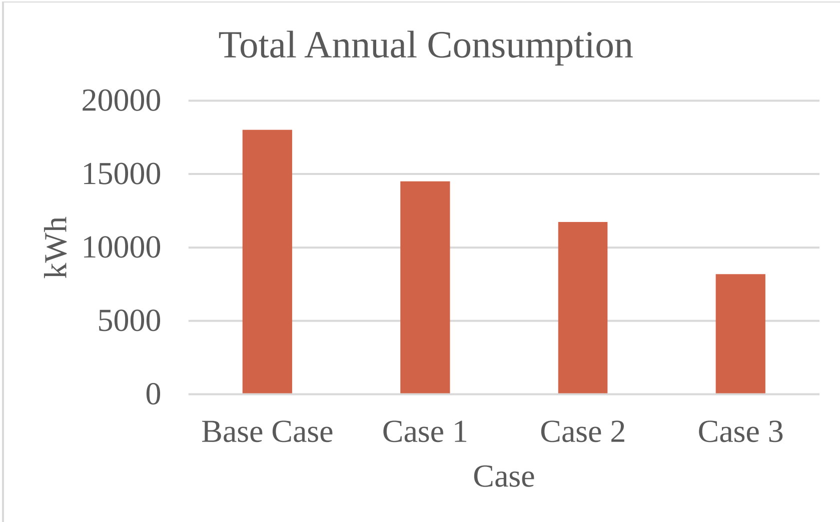


Figure 5.7 Comparison between annual energy consumption of Cases

It can clearly be established from Figure 5.7 that energy conservation measures are highly efficient in reducing annual energy consumption.

Table 5.9 Comparative analysis between Cases

Case	Annual Energy Consumption	% difference from Base Case
Base Case	18,011 kWh	-
Case 1	14,495 kWh	-19.52%
Case 2	11,733 kWh	-34.86%
Case 3	8,190 kWh	-54.53%

The lowest annual energy consumption is from Case 3. It is a 54% reduction in energy consumption from Base Case energy simulation results.

Table 5.10 Comparative analysis by system

System	Base Case	Case 1	%diff	Case 2	%diff	Case 3	%diff
Space Heating	11.36	8.00	-29.58%	11.89	4.67%	8.53	-24.91%
Cooling	2.52	2.39	-5.16%	2.45	-2.78%	2.25	-10.71%
Hot Water	1.56	1.56	0.00%	1.56	0.00%	1.56	0.00%
Plug Loads	0.91	0.91	0.00%	0.91	0.00%	0.91	0.00%
Lighting	1.62	1.62	0.00%	0.59	-63.58%	0.59	-63.58%
Total	17.97	14.48	-19.42%	17.4	-3.17%	13.84	-22.98%
PV	0	0.00	-	-5.695		-5.695	
Total after PV	17.97	14.48	-19.42%	11.705	-34.86%	8.145	-54.67%

Without PV systems, Case 2 would have shown only a 3.24% reduction from Base Case. The researcher has identified earlier also that PV systems alone account for a 31% reduction in energy from Base Case.

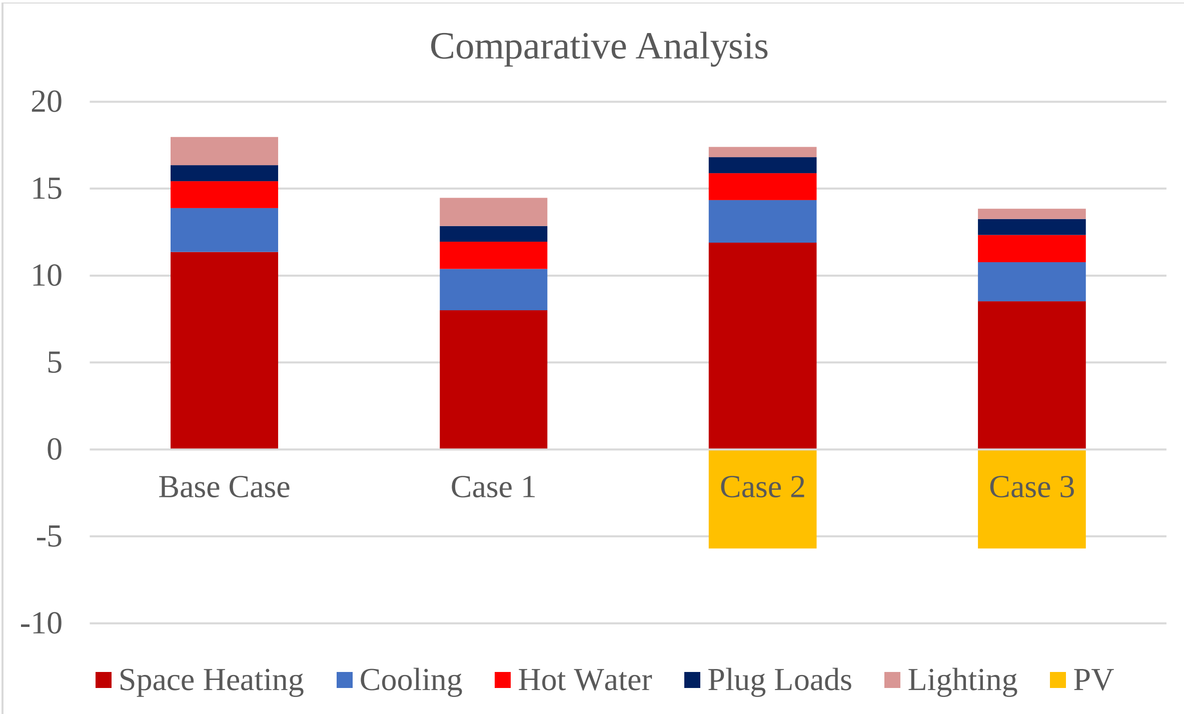


Figure 5.8 Comparative analysis by system

While this comparative analysis is a crucial part of this research, the researcher's aim is to choose between the three cases based on the Life Cycle Cost Analysis of each case. The next section uses the same energy conservation data to calculate life cycle costs for each of these systems to establish economic benefits.

5.2 Life Cycle Cost Analysis

The energy consumption data discussed in the previous section will now be used to present the findings from the life cycle cost analysis of each case over a span of 50 years. The annual operations and maintenance cost, installation cost, discount rate and life-span of the systems discussed in the previous sections is summarized in the sections to follow.

5.2.1 Common Inputs

Project Location: West Lafayette, IN

Discount Rate: 3%

Building Economic Life: 50 years

Electricity Rate: $0.12 per kWh

Annual Cost Escalation for electricity: 3%

5.2.2 Exterior Wall Thermal Insulation Inputs

Area: 978.65 Sq. ft.

Base Case installation cost: $0.64 /sq. ft.

Case 2 installation cost: $1.35 /sq. ft.

Life Span: 50 years

5.2.3 Window Glazing Inputs

Area: 97 sq. ft.

Base Case installation cost: $21.86 /sq. ft.

Case 2 installation cost: 29.65 /sq. ft.

Life Span: 40 years

5.2.4 Lighting Fixtures Inputs

Incandescent lighting installation cost: $0.76 /each

Life Span (Incandescent): 1 year

LED lighting installation cost: $1.56 /each

Life Span (LED): 14 years

5.2.5 HVAC Inputs

Base case HVAC replacement cost: $2109

Case 3 HVAC replacement cost: $2595

Life Span: 15 years

5.2.6 Photovoltaic System Inputs

Installation cost: 12.65 /kWh/year

Life Span: 25 years

5.2.7 LCCA Comparison by Case

Net present value calculated for all systems over a lifespan of 50 years

5.2.7.1 Base Case LCCA

Table 5.11 LCCA Results – Base Case

System	Base Case Life Cycle Cost
Thermal Insulation & Window Glazing	$11,921.47
Lighting	$4,538.80
HVAC	$44,955.47
PV System	$-
Total	$61,415.74

Base case has an NPV of $61,415. HVAC accounts for the highest share of life cycle cost because of high installation costs & higher O&M costs. Followed by Insulation & glazing. Lighting does not significantly impact the total, but it has potential for savings.

5.2.7.2 Case 1 LCCA

Table 5.12 LCCA Results – Case 1

System	Case 1 Life Cycle Cost
Thermal Insulation & Window Glazing	$4,730.64
Lighting	$4,538.80
HVAC	$44,955.47
PV System	$-
Total	$54,224.91

Case 1 shows a drop by 11.71% in lifecycle costs as compared to the Base Case. With the addition of better thermal insulation & Glazing in Case 1, Total NPV reduces to $54,224.91. HVAC still holds the highest share in life cycle cost, but a higher thermal mass and better glazing system result in lower energy bills over the building's lifespan.

5.2.7.3 Case 2 LCCA

Table 5.13 LCCA Results – Case 2

System	Case 2 Life Cycle Cost
Thermal Insulation & Window Glazing	$11,921.47
Lighting	$1,601.39
HVAC	$47,982.93
PV System	$(1,190.92)
Total	$60,314.87

Compared to the Base Case, Case 2 only shows a drop by 1.79% in life cycle cost, but it uses active measures for energy conservation and production. There is a significant energy production and energy saving due to the use of high efficiency lighting system but, due to the high installation & operation costs of HVAC system, NPV is not significantly lower.

5.2.7.4 Case 3 LCCA

Table 5.14 LCCA Results – Case 3

System	Case 2 Life Cycle Cost
Thermal Insulation & Window Glazing	$4,730.64
Lighting	$1,601.39
HVAC	$47,982.93
PV System	$(1,190.92)
Total	$53,124.04

With a drop of life cycle costs by 13.5% compared to Base Case, Case 3 shows the highest reduction in life cycle costs. Case 3 employees passive & active EEMs for energy conservation. Case 3 has the lowest NPV amongst all.

5.2.8 Comparative Analysis

5.2.8.1 By System

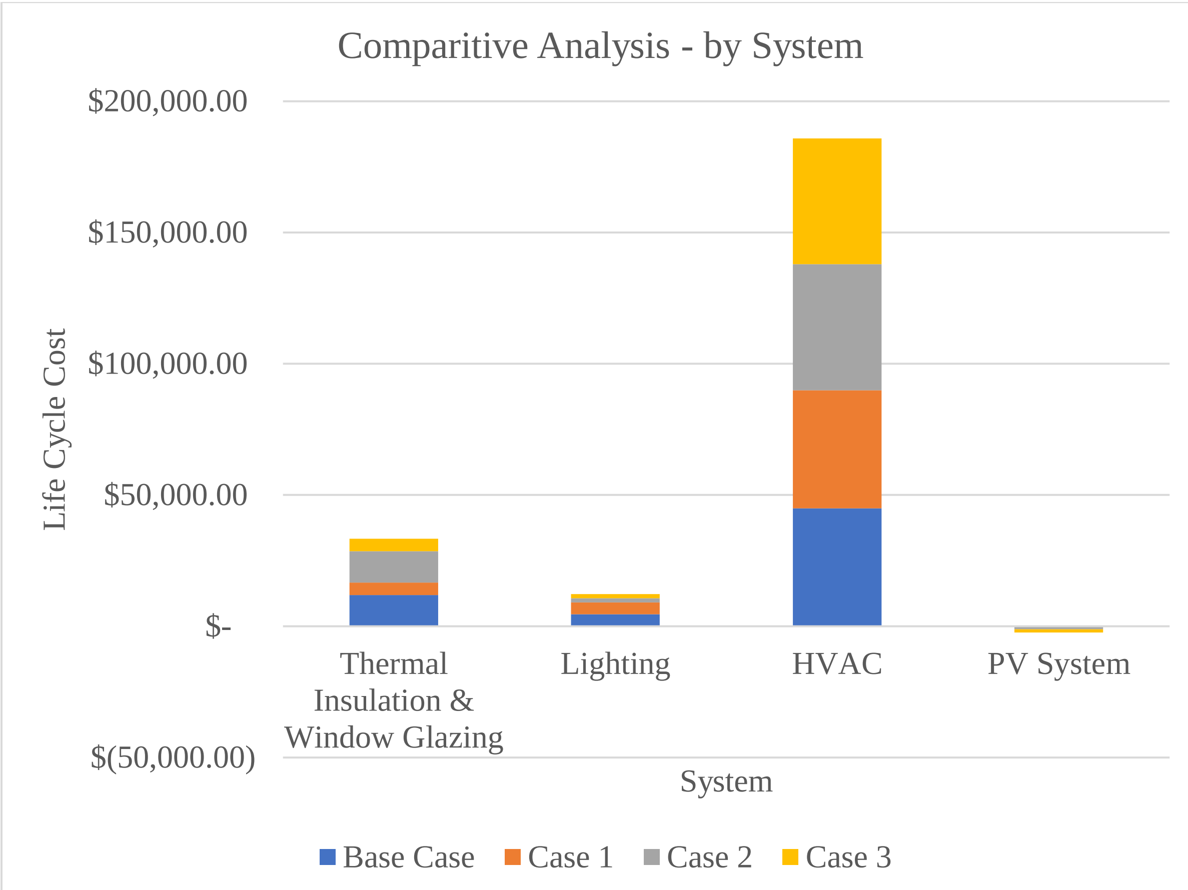


Figure 5.9 Comparative Analysis by System- Life Cycle Cost

The researcher has highlighted the fact that insulation & glazing having a significant effect. With the increased efficiency of the building envelope, there is significantly less need for heating & cooling, resulting in lesser energy consumption. However, the same cannot be said for a high efficiency HVAC system. With the high efficiency, one still faces high prices and it does not significantly affect energy consumption. Over the lifespan of the building, this gets even more insignificant. Coupled with a better building envelope in Case 3 however, the HVAC system performs better. A conclusion drawn here is that costly energy systems are not always as effective.

5.2.8.2 By Case

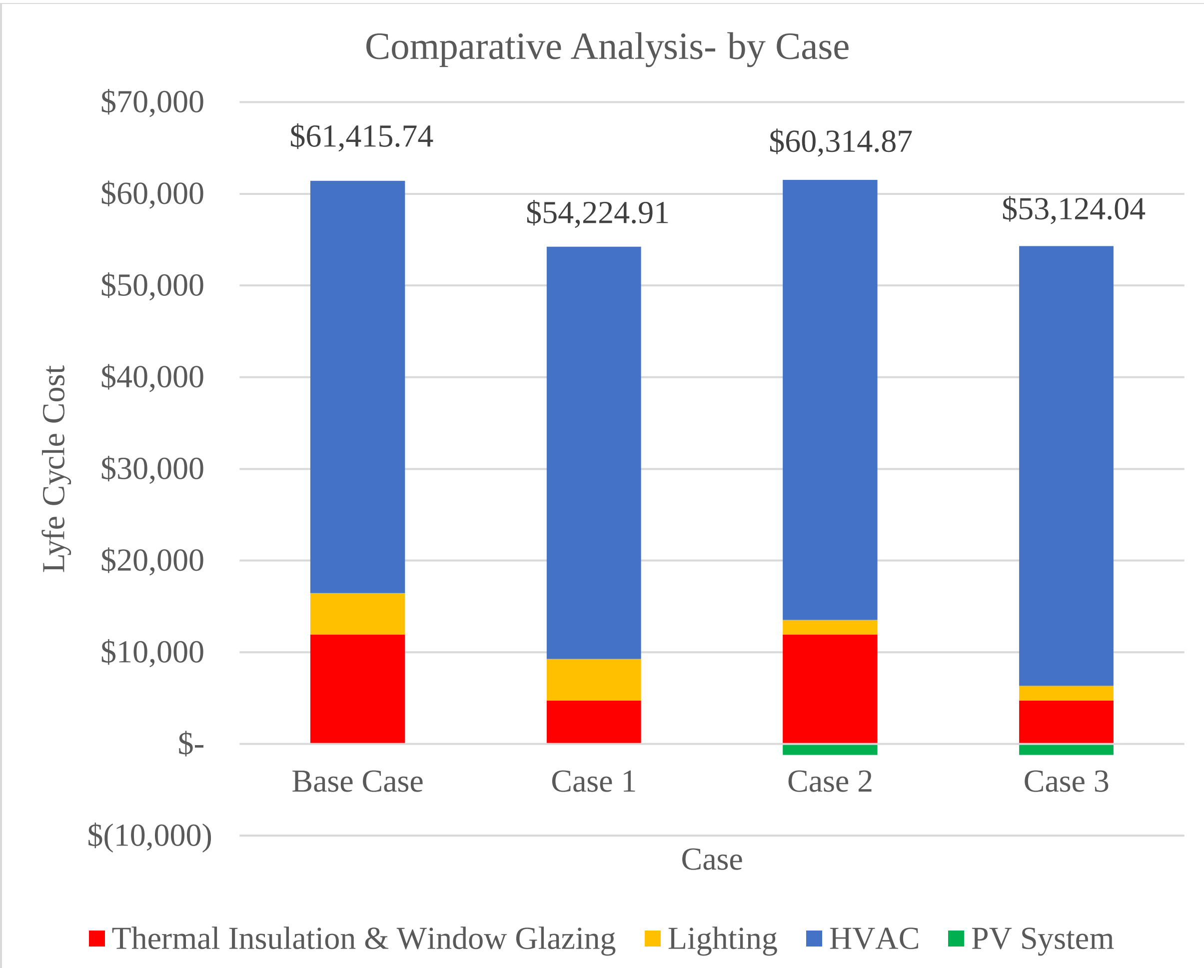


Figure 5.10 Comparative Analysis by Case – Life Cycle Cost

Overall, investment in EEMs does pay off. Base case has the highest NPV. Case 2 includes Active EEMs and has the second highest NPV suggesting that Passive energy conservation measures (Case 2) are better than Active energy consumption ones. The lowest NPV is for Case 3, which employs both, passive and active measures, giving the best results in terms of energy conservation and cost benefits. An alternate case could be Case 1 coupled with a PV system and analyzed to see the LCCA and cost benefits of that system giving the long-term cost benefits of a simple PV system addition to an existing residential building.

5.2.8.3 Energy Consumption and LCCA

In the previous sections the researcher has presented a comparative analysis of energy consumption between the different cases and of life cycle cost analysis between different cases. This section outlines the difference in energy consumption between the cases and their corresponding life cycle cost in the table below:

Table 5.15 Comparative Analysis – Energy Consumption and LCCA

Case	**Annual Energy Consumption**	**% difference from Base Case**	**Life Cycle Cost**	**% difference from Base Case**
Base Case	18,011 kWh	-	$61,415.74	-
Case 1	14,495 kWh	↓-19.52%	$54,224.91	↓ -11.71%
Case 2	11,733 kWh	↓ -34.86%	$60,314.87	↓ -1.79%
Case 3	8,190 kWh	↓ -54.53%	$53,124.04	↓ -13.50%

While the energy consumption in Case 1 is 19% lower than the base case, its life cycle cost is almost 12% lower. This signifies that passive measures give a commensurate reduction in energy consumption while also paying off economically in the long run. In Case 2, energy consumption is reduced by almost 35% but the life cycle cost only by 2%. Active measures, while reducing energy consumption, cost about the same as the equipment in Base Case. When compared to Case 1, economically, Case 2 does not show any significant savings. With lowest energy consumption and the lowest life cycle cost, Case 3 is the most beneficial option to reduce energy consumption.

5.2.8.4 Initial Costs and Life cycle costs

The following tables outline the initial costs for each case and the life cycle cost. This is of interest to investors and stakeholders when making decisions. The initial cost for the Base Case is the lowest however, the life cycle cost of the Base Case is the highest.

Table 5.16 Initial costs and life cycle costs for each case

	Base Case	**Case 1**	**Case 2**	**Case 3**
Initial Cost	$4,875.00	$6,325.47	$15,453.26	$16,903.74
Life Cycle Cost	$61,415.74	$54,224.91	$60,314.87	$53,124.04

5.3 Summary

This chapter has presented the results of the energy simulation and of the Life Cycle Cost Analysis performed for the four different cases. The researcher has identified the energy conservation measures having a significant impact on annual energy consumption and on life cycle costs. The researcher has compared each of the cases with the Base Case to establish the difference in energy consumption and life cycle cost between active and passive measures and a combination of both.

CHAPTER 6. CONCLUSION

After having analyzed the results, the researcher has, in this chapter, organized the conclusions that can be made from the data. With this study, the researcher aimed to help make decisions regarding selection of systems in a residential building through energy simulation and Life Cycle Cost Analysis. The researcher has discussed the implication of the results in this chapter. The researcher has also identified further research that can be conducted in this area to improve the adoption of LCCA for green building strategies.

6.1 Discussions

The aim of this research was to study the economic payoff of making energy efficient choices in a residential building over its life cycle. The researcher used energy simulation tools along with Life Cycle Costing to establish these economic benefits.

For the first research question, the researcher has established the significance of energy conservation measures by using the energy simulation data from the base case and the study of literature. Space heating & cooling accounts for maximum energy consumption, followed by lighting and water heating. Energy simulation for all three cases show similar results. In the base case however, energy consumption through HVAC is significantly higher than previous studies. The researcher chose HVAC system and lighting fixtures as the two active measures of energy conservation. Furthermore, from the results of the energy simulations done for the Base Case and Case 2 (active measures only) the researcher has found a difference in energy consumption of 583 kWh per year. Case 3 (both active and passive) included active measure changes like change in the Energy Efficiency Ratio of the HVAC system and changing all lighting fixtures in the apartment to LED. This translates to an annual savings amount of $70. The figure is not as high as the researcher had hoped for but that can be attributed tenant behavior and high installation costs. The heating & cooling set points play a huge role in energy consumption for HVAC systems.

After performing Life Cycle Cost Analysis of the three cases and comparing them to the base case, the researcher has concluded that, for the most part new energy consuming equipment implies more energy savings which in turn is expected to pay off over the life span of the building. It is more prudent to invest in an improved insulation system than a more efficient HVAC system.

The addition of an energy generating system like Photovoltaic systems in Case 2 & Case 3 reduces annual consumption greatly (for similar locations) but incurs higher installation costs. Keeping in mind the energy savings potential of PV systems, they are an economically robust investment. In conclusion, owners and tenants, with the means to do so, should prefer energy generation and passive conservation.

The researcher also stresses upon the use of energy modelling and LCCA during the design phase. Integrating energy modelling, energy simulation tools and Life Cycle Cost Analysis would result in greater accuracy. Moreover, the researcher has only used 3 alternatives to a Base Case with specific changes, where these tools can be used to create numerous alternatives for clients, architects and engineers to choose from.

6.2 Limitations

The energy model created has an accuracy of more than 90%. There are many factors that have affected the model's accuracy like:

- Weather files for eQUEST (file extension .bin) are only available for cities with major airports. In this case, the closest location was Indianapolis. While it lies in the same climatic region, there are daily variation in the weather. Since eQUEST performs hourly simulation, it affects the annual consumption as well.

- The software itself has input limitations as well. eQUEST has predefined values that cannot be overridden. The design wizard used for this study only allows creation of multi-family buildings rather than individual apartments. The researcher has used the available inputs to create a model suitable for multi-family apartment. While results show an accuracy greater than 90%, higher accuracy would be achieved if these inputs could be modified or overridden.
- Most significantly, user behavior cannot be predicted by this software, which plays a major role in energy consumption, especially for residences where occupancy is a hundred percent throughout the calendar year. Even though eQUEST has hourly input, which the researcher has carefully observed and noted during the course of this study for eQUEST inputs, there are variations in the actual occupant behavior through the year.
- Another factor related to this is occupant comfort. Even with predefined inputs for tenant comfort, there will always be difference between the actual behavior and simulation output.
- Life Cycle Cost analysis is a constantly evolving area of economic analysis. The challenge is that numerous technological advancements are being made constantly and LCCA is being performed for 50 years in this research. New developments could lead to better solutions and compromise the accuracy of this study’s predictions.
- The spreadsheet from California State University used for calculating Life Cycle Costs had built-in formulae and a different method of calculating Life Cycle Costs could result in different numbers.

6.3 Recommendation for Future Studies

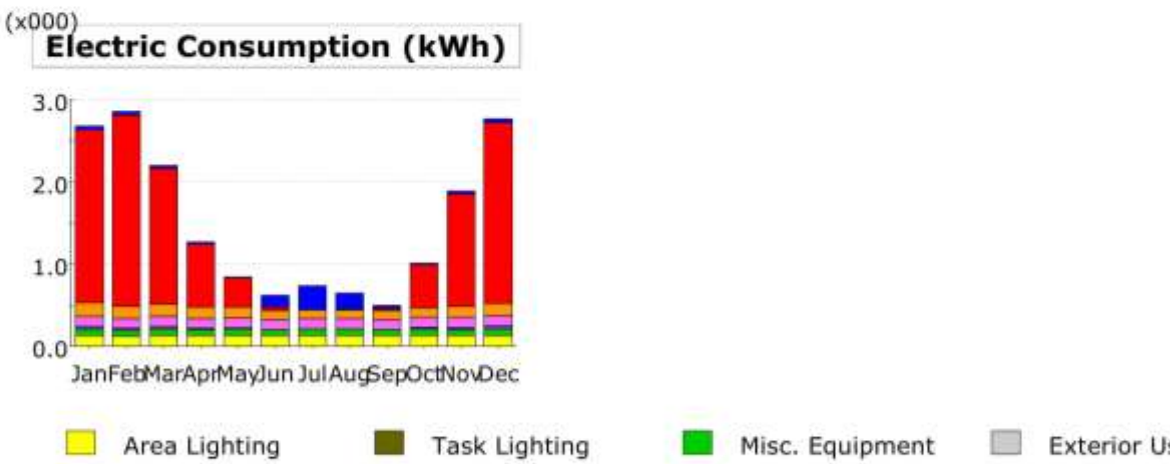
The researcher has only used one energy simulation software with an accuracy of 90% to the actual energy consumption. For future studies, more software simulation tools can be explored that provide a more accurate model and have the ability to analyze PV systems along with other energy conservation measures.

This research has established that changing HVAC system's Energy Efficiency Ratio has not had an impact on energy savings and future studies could explore other aspects of HVAC usage like, temperature set points, duct material, system type etc.

This research does not include tenant comfort as a parameter in conducting the Life Cycle Cost Analysis. Through this study, the researcher has observed that occupants play a huge role in residential energy consumption. Studies can be performed exploring the role of occupant behavior in energy saving and the consequent effect over the life cycle of the building.

APPENDIX A. SIMULATION AND REPORTS

Project/Run: BCM 01 R8 - Baseline Design | Run Date/Time: 03/31/19 @ 22:22



Electric Consumption (kWh x000)

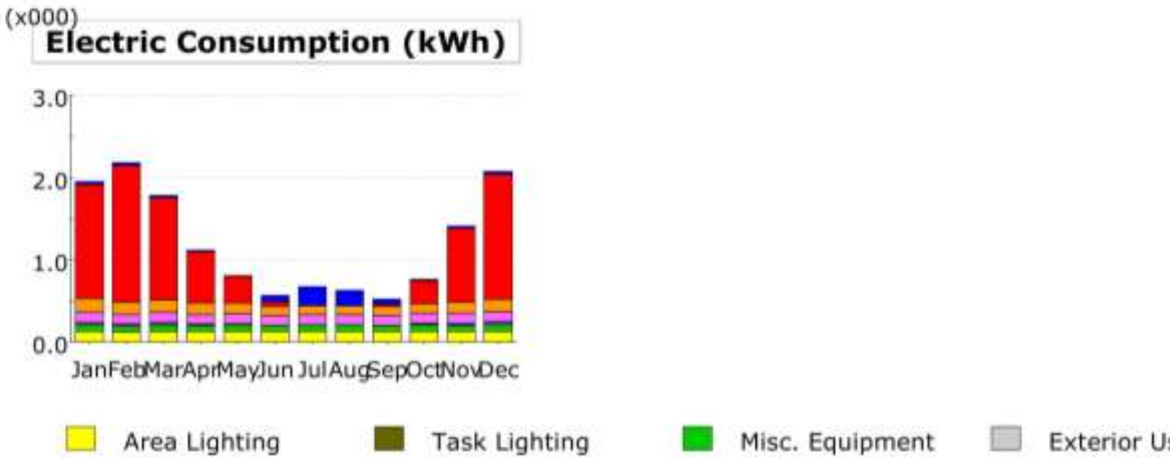
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	0.04	0.04	0.04	0.02	0.01	0.14	0.30	0.20	0.03	0.02	0.03	0.04	0.92
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	2.10	2.33	1.64	0.76	0.36	0.04	0.00	0.01	0.03	0.52	1.37	2.20	11.36
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	0.16	0.15	0.16	0.14	0.13	0.11	0.10	0.10	0.10	0.12	0.13	0.16	1.58
Vent. Fans	0.12	0.11	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	1.46
Pumps & Aux.	0.03	0.03	0.03	0.01	0.01	0.00	0.00	0.00	0.00	0.01	0.03	0.03	0.18
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	0.08	0.07	0.08	0.07	0.08	0.07	0.08	0.08	0.07	0.08	0.07	0.08	0.90
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	0.14	0.12	0.14	0.13	0.14	0.13	0.14	0.14	0.13	0.14	0.13	0.14	1.61
Total	2.68	2.85	2.20	1.27	0.84	0.62	0.74	0.65	0.50	1.01	1.89	2.77	18.01

Gas Consumption (Btu)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool													
Heat Reject.													
Refrigeration													
Space Heat													
HP Supp.													
Hot Water													
Vent. Fans													
Pumps & Aux.													
Ext. Usage													
Misc. Equip.													
Task Lights													
Area Lights													
Total													

eQUEST 3.65.7175 | Monthly Energy Consumption by Enduse | Page 1

Figure A.1 Base Case Energy Simulation Report



Electric Consumption (kWh x000)

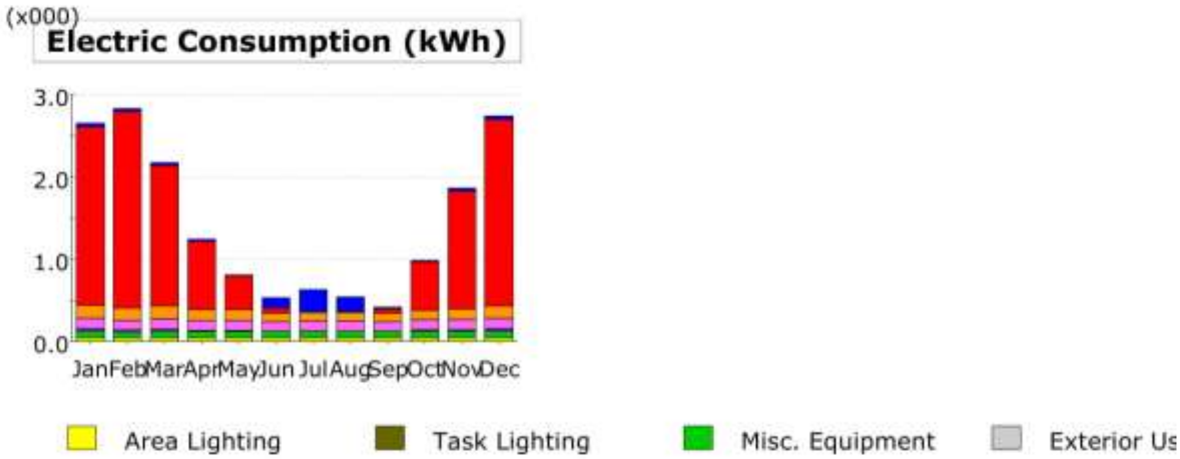
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	0.03	0.04	0.03	0.02	0.01	0.08	0.23	0.18	0.07	0.02	0.03	0.04	0.77
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	1.38	1.66	1.24	0.62	0.32	0.05	0.00	0.01	0.03	0.27	0.90	1.52	7.99
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	0.16	0.15	0.16	0.14	0.13	0.11	0.10	0.10	0.10	0.12	0.13	0.16	1.58
Vent. Fans	0.12	0.11	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	1.46
Pumps & Aux.	0.03	0.03	0.03	0.01	0.01	0.00	0.00	0.00	0.00	0.01	0.03	0.03	0.18
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	0.08	0.07	0.08	0.07	0.08	0.07	0.08	0.08	0.07	0.08	0.07	0.08	0.90
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	0.14	0.12	0.14	0.13	0.14	0.13	0.14	0.14	0.13	0.14	0.13	0.14	1.61
Total	1.95	2.18	1.79	1.12	0.81	0.57	0.67	0.63	0.53	0.77	1.41	2.08	14.49

Gas Consumption (Btu)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool													
Heat Reject.													
Refrigeration													
Space Heat													
HP Supp.													
Hot Water													
Vent. Fans													
Pumps & Aux.													
Ext. Usage													
Misc. Equip.													
Task Lights													
Area Lights													
Total													

Figure A.2 Case 1 Energy Simulation Results

Project/Run: BCM 01 R8 - 4 Run Date/Time: 03/31/19 @ 22:22



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	0.04	0.04	0.04	0.02	0.01	0.12	0.28	0.18	0.02	0.02	0.03	0.04	0.85
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	2.17	2.39	1.71	0.82	0.41	0.06	0.00	0.01	0.05	0.58	1.43	2.26	11.89
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	0.16	0.15	0.16	0.14	0.13	0.11	0.10	0.10	0.10	0.12	0.13	0.16	1.58
Vent. Fans	0.12	0.11	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	1.46
Pumps & Aux.	0.03	0.03	0.03	0.01	0.01	0.00	0.00	0.00	0.00	0.01	0.03	0.03	0.18
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	0.08	0.07	0.08	0.07	0.08	0.07	0.08	0.08	0.07	0.08	0.07	0.08	0.90
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	0.05	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.57
Total	2.65	2.83	2.18	1.24	0.81	0.53	0.63	0.54	0.42	0.98	1.86	2.74	17.43

Gas Consumption (Btu)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool													
Heat Reject.													
Refrigeration													
Space Heat													
HP Supp.													
Hot Water													
Vent. Fans													
Pumps & Aux.													
Ext. Usage													
Misc. Equip.													
Task Lights													
Area Lights													
Total													

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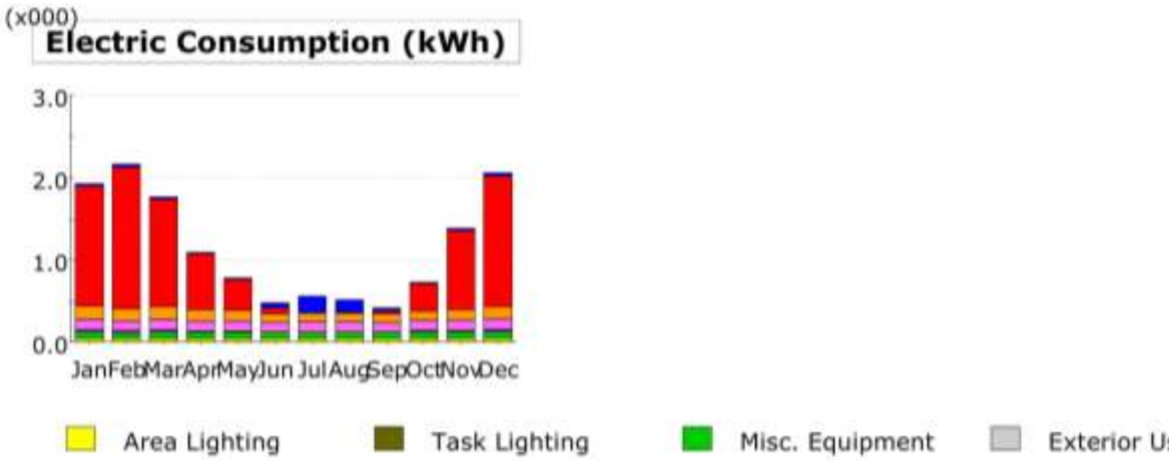
Figure A.3 Case 2 Energy Simulation Report

Project/Run: BCM 01 R8 - 5 Run Date/Time: 03/31/19 @ 22:23



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	0.03	0.04	0.03	0.02	0.01	0.05	0.20	0.15	0.03	0.01	0.03	0.04	0.66
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	1.45	1.72	1.30	0.68	0.38	0.07	0.00	0.01	0.04	0.33	0.96	1.59	8.54
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	0.16	0.15	0.16	0.14	0.13	0.11	0.10	0.10	0.10	0.12	0.13	0.16	1.58
Vent. Fans	0.12	0.11	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	1.46
Pumps & Aux.	0.03	0.03	0.03	0.01	0.01	0.00	0.00	0.00	0.00	0.01	0.03	0.03	0.18
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	0.08	0.07	0.08	0.07	0.08	0.07	0.08	0.08	0.07	0.08	0.07	0.08	0.90
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	0.05	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.57
Total	1.93	2.17	1.77	1.10	0.78	0.47	0.56	0.52	0.42	0.72	1.39	2.06	13.88

Gas Consumption (Btu)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool													
Heat Reject.													
Refrigeration													
Space Heat													
HP Supp.													
Hot Water													
Vent. Fans													
Pumps & Aux.													
Ext. Usage													
Misc. Equip.													
Task Lights													
Area Lights													
Total													

eQUEST 3.65.7175 Monthly Energy Consumption by Enduse Page 1

Figure A.4 Case 3 Energy Simulation Report

NREL

Caution: Photovoltaic system performance predictions calculated by PVWatts® include many inherent assumptions and uncertainties and do not reflect variations between PV technologies nor site-specific characteristics except as represented by PVWatts® inputs. For example, PV modules with better performance are not differentiated within PVWatts® from lesser performing modules. Both NREL and private companies provide more sophisticated PV modeling tools (such as the System Advisor Model at https://sam.nrel.gov) that allow for more precise and complex modeling of PV systems.

The expected range is based on 30 years of actual weather data at the given location and is intended to provide an indication of the variation you might see. For more information, please refer to this NREL report: The Error Report.

The energy output range is based on analysis of 30 years of historical weather data for nearby , and is intended to provide an indication of the possible interannual variability in generation for a Fixed (open rack) PV system at this location.

RESULTS

5,696 kWh/Year*

System output may range from 5,452 to 5,842 kWh per year near this location.

Month	Solar Radiation (kWh / m² / day)	AC Energy (kWh)	Value ($)
January	2.91	327	34
February	3.69	367	38
March	4.72	497	51
April	5.58	556	57
May	6.05	615	63
June	6.38	596	61
July	6.47	619	64
August	6.11	581	60
September	5.54	521	54
October	4.12	424	44
November	3.15	331	34
December	2.33	261	27
Annual	**4.75**	**5,695**	**$ 587**

Location and Station Identification

Requested Location	300 North Salisbury Street, West Lafayette, Indiana
Weather Data Source	Lat, Lon: 40.41, -86.9 1.1 mi
Latitude	40.41° N
Longitude	86.9° W

PV System Specifications *(Residential)*

DC System Size	4.2 kW
Module Type	Standard
Array Type	Fixed (open rack)
Array Tilt	20°
Array Azimuth	180°
System Losses	14.08%
Inverter Efficiency	96%
DC to AC Size Ratio	1.2

Economics

Average Retail Electricity Rate	0.103 $/kWh

Performance Metrics

Capacity Factor	15.5%

Figure A.5 PVWatts® Calculator Output

APPENDIX B. LIFE CYCLE COST CALCULATIONS

Summary inputs

Project:	Thesis Research	Location:	West Lafayette	Date:	10-03-19
Prepared by:	Ayushi Hajare				
Address:	West Lafayette, IN				

ASSUMPTIONS

Electrical Energy Cost:	$0.12	per kwh
Electrical Cost Annual Escalation:	3%	
Natural Gas cost:	$0.75	per Therm
Natural Gas Cost Annual Escalation:	2%	
Discount Rate:	7%	
Building Economic Life:	50	years

BUILDING ENVELOPE #1

Envelope Alt #1	**Envelope Alt #1** Existing Wall system							
Installed Cost	Initial Cost						Estimated Cost	Present Worth
	Installed Cost						$2,747	$2,747
	TOTAL INITIAL COST							$2,747
Replacement Costs		Building Component	Sq.ft.	Installed cost per sq.ft.	Life Years	Replacement Cost Factor	Replacement Cost	Present Worth
	70	Existing Wall Type U 0.1	978.65	$0.64	50	0.0000	$626	$0
	73	1/4" single pane plain glass	97	$21.86	40	0.1131	$2,120	$240
	0	N/A			0		$0	$0

	0	N/A			0		$0	$0
	0	N/A			0		$0	$0
	0	N/A			0		$0	$0
	0	N/A			0		$0	$0
	0	N/A			0		$0	$0
	0	N/A			0		$0	$0
	0	N/A			0		$0	$0
	Totals						$2,747	
	TOTAL PRESENT WORTH OF REPLACEMENT COST							$240
Annual Costs	Annual Costs				cost per sq.ft.	Present Worth Factor	Annual cost	Present Worth
	Maintenance Cost			sq.ft.		25.7298		
	70	Existing Wall Type U 0.1		978.65	0.0725		$71	$1,826
	73	1/4" single paine plain glass		97	2.8485		$276	$7,109
	0	N/A		0	0		$0	$0
	0	N/A		0	0		$0	$0
	0	N/A		0	0		$0	$0
	0	N/A		0	0		$0	$0
	0	N/A		0	0		$0	$0
	0	N/A		0	0		$0	$0
	0	N/A		0	0		$0	$0
	0	N/A		0	0		$0	$0
	Electrical Energy				0	kwh	$0	$0
	Natural Gas				0	therms	$0	$0
	TOTAL PRESENT WORTH OF ANNUAL COST							$8,935
LCC	**TOTAL PRESENT WORTH LIFE CYCLE COST**						**$11,921**	

BUILDING ENVELOPE #2

Envelope Alt #2	**Envelope Alt #2**		
Installed Cost	Initial Cost	Estimated Cost	Present Worth
	Installed Cost	$4,197	$4,197

	TOTAL INITIAL COST							$4,197
Replacement Costs	Building Component		sq. ft.	Installed cost/sq.ft.	Life Years	Replacement Cost Factor	Replacement Cost	Present Worth
	71	New Wall Type U 0.404	978.65	$1.35	50	0.0000	$1,321	$0
	78	Low e glass	97	$29.65	40	0.1131	$2,876	$325
	0	N/A			0	-0.1942	$0	$0
	0	N/A			0	-0.1942	$0	$0
	0	N/A			0	-0.1942	$0	$0
	0	N/A			0	-0.1942	$0	$0
	0	N/A			0	-0.1942	$0	$0
	0	N/A			0	-0.1942	$0	$0
	0	N/A			0	-0.1942	$0	$0
	0	N/A			0	-0.1942	$0	$0
	Totals						$4,197	
	TOTAL PRESENT WORTH OF REPLACEMENT COST							$325
Annual Costs	Annual Costs				cost per sq.ft.	Present Worth Factor	Annual cost	Present Worth
	Maintenance Cost			sq.ft.		25.7298		
	71	New Wall Type U 0.404		978.65	0.0725		$71	$1,826
	78	Low e glass		97	2.8485		$276	$7,109
	0	N/A		0	0		$0	$0
	0	N/A		0	0		$0	$0
	0	N/A		0	0		$0	$0
	0	N/A		0	0		$0	$0
	0	N/A		0	0		$0	$0
	0	N/A		0	0		$0	$0
	0	N/A		0	0		$0	$0
	0	N/A		0	0		$0	$0
	Electrical Energy				-3318	kwh	-$398	-$8,727
	Natural Gas					therms	$0	$0
	TOTAL PRESENT WORTH OF ANNUAL COST							$208
LCC	**TOTAL PRESENT WORTH LIFE CYCLE COST**						**$4,731**	

HEATING VENTILATING AND AIR CONDITIONING (HVAC)

HVAC Alt #1	HVAC Alt #1					
Installed Cost	Initial Cost				Estimated Cost	Present Worth
	Installed Cost				$2,109	$2,109
	TOTAL INITIAL COST					$2,109
Replacement Costs	Replacement Costs		Life Years	Replacement Cost Factor	Replacement Cost	Present Worth
	3	Residential package AC Unit	15	1.1553	$2,109	$2,437
		N/A	0			$0
		N/A	0			$0
		N/A	0			$0
		N/A	0			$0
		N/A	0			$0
		N/A	0			$0
		N/A	0			$0
		N/A	0			$0
		N/A	0			$0
	Totals				$2,109	
	TOTAL PRESENT WORTH OF REPLACEMENT COST					$2,437
Annual Costs	Annual Costs		% of initial cost	Present Worth Factor	Annual cost	Present Worth
	Maintenance Cost			25.7298		
	3	Residential package AC Unit	0.07		$148	$3,798
	0	N/A	0		$0	$0
	0	N/A	0		$0	$0
	0	N/A	0		$0	$0
	0	N/A	0		$0	$0
	0	N/A	0		$0	$0
	0	N/A	0		$0	$0

	0	N/A	0		$0	$0
	0	N/A	0		$0	$0
	0	N/A	0		$0	$0
	Electrical Energy		13920	kwh	$1,670	$36,611
	Natural Gas			therms	$0	$0
	TOTAL PRESENT WORTH OF ANNUAL COST					$40,410
LCC	**TOTAL PRESENT WORTH LIFE CYCLE COST**				**$44,955**	

HEATING VENTILATING AND AIR CONDITIONING (HVAC)

HVAC Alt #2	**HVAC Alt #2**					
Installed Cost	Initial Cost				Estimated Cost	Present Worth
	Installed Cost				$2,595	$2,595
	TOTAL INITIAL COST					$2,595
Replacement Costs	Replacement Costs		Life Years	Replacement Cost Factor	Replacement Cost	Present Worth
	3	Residential package AC Unit	15	1.1553	$2,595	$2,998
		N/A	0			$0
		N/A	0			$0
		N/A	0			$0
		N/A	0			$0
		N/A	0			$0
		N/A	0			$0
		N/A	0			$0
	0	N/A	0			$0
	0	N/A	0			$0
	Totals				$2,595	
	TOTAL PRESENT WORTH OF REPLACEMENT COST					$2,998
Annu	Annual Costs		% of initial cost	Present Worth Factor	Annual cost	Present Worth

	Maintenance Cost			25.7298		
	3	Residential package AC Unit	0.07		$182	$4,674
	0	N/A	0		$0	$0
	0	N/A	0		$0	$0
	0	N/A	0		$0	$0
	0	N/A	0		$0	$0
	0	N/A	0		$0	$0
	0	N/A	0		$0	$0
	0	N/A	0		$0	$0
	0	N/A	0		$0	$0
	0	N/A	0		$0	$0
	Electrical Energy		14340	kwh	$1,721	$37,716
	Natural Gas			therms	$0	$0
	TOTAL PRESENT WORTH OF ANNUAL COST					$42,390
LCC	**TOTAL PRESENT WORTH LIFE CYCLE COST**				**$47,983**	

ELECTRICAL LIGHTING

Lighting Alt #1	**Lighting Alt #1** Lighting – LEDs and Incandescent					
Installed Cost	Initial Cost				Estimated Cost	Present Worth
	Installed Cost				$19	$19
	TOTAL INITIAL COST					$19
Replacement Costs	Replacement Costs		Life Years	Replacement Cost Factor	Replacement Cost	Present Worth
	81	LED Lights	13.7	1.4194	$9	$13
	82	Incandescent lighting	1	25.5017	$10	$252
	0	N/A	0		$0	$0
	0	N/A	0		$0	$0
	0	N/A	0		$0	$0
	0	N/A	0		$0	$0
	0	N/A	0		$0	$0
	0	N/A	0		$0	$0
	0	N/A	0			$0
	0	N/A	0			$0
	Totals				$19	
	TOTAL PRESENT WORTH OF REPLACEMENT COST					$265
Annual Costs	Annual Costs		% of initial cost	Present Worth Factor	Annual cost	Present Worth
	Maintenance Cost			25.7298		
	81	LED Lights	0.04		$0	$10
	82	Incandescent lighting	0.04		$0	$10
	0	N/A	0		$0	$0
	0	N/A	0		$0	$0
	0	N/A	0		$0	$0
	0	N/A	0		$0	$0
	0	N/A	0		$0	$0
	0	N/A	0		$0	$0
	0	N/A	0		$0	$0

	0	N/A	0		$0	$0
	Electrical Energy		1610	kwh	$193	$4,235
	Natural Gas			therms	$0	$0
	TOTAL PRESENT WORTH OF ANNUAL COST					$4,254
LCC	**TOTAL PRESENT WORTH LIFE CYCLE COST**				**$4,539**	

Lighting Alt #2	**Lighting Alt #2** Only LEDs					
Installed Cost	Initial Cost				Estimated Cost	Present Worth
	Installed Cost				$30	$30
	TOTAL INITIAL COST					$30
Replacement Costs	Replacement Costs		Life Years	Replacement Cost Factor	Replacement Cost	Present Worth
	0	N/A	0	-0.1942	$0	$0
	81	LED Lights	13.7	1.4194	$30	$42
		N/A	0	-0.1942		$0
	0	N/A	0	-0.1942	$0	$0
	0	N/A	0	-0.1942	$0	$0
	0	N/A	0	-0.1942	$0	$0
	0	N/A	0	-0.1942	$0	$0
	0	N/A	0	-0.1942	$0	$0
	0	N/A	0	-0.1942		$0
	0	N/A	0	-0.1942		$0
	Totals				$30	
	TOTAL PRESENT WORTH OF REPLACEMENT COST					$42
Annual Costs	Annual Costs		% of initial cost	Present Worth Factor	Annual cost	Present Worth
	Maintenance Cost			25.7298		
	0	N/A	0		$0	$0

	81	LED Lights	0.04		$1	$31
	0	N/A	0		$0	$0
	0	N/A	0		$0	$0
	0	N/A	0		$0	$0
	0	N/A	0		$0	$0
	0	N/A	0		$0	$0
	0	N/A	0		$0	$0
	0	N/A	0		$0	$0
	0	N/A	0		$0	$0
	Electrical Energy		570	kwh	$68	$1,499
	Natural Gas			therms	$0	$0
	TOTAL PRESENT WORTH OF ANNUAL COST					$1,530
LCC	**TOTAL PRESENT WORTH LIFE CYCLE COST**				**$1,601**	

Photovoltaic System

PV System	PV System					
Installed Cost	Initial Cost				Estimated Cost	Present Worth
	Installed Cost				$8,450	$8,450
	TOTAL INITIAL COST					$8,450
Replacement Costs	Replacement Costs		Life Years	Replacement Cost Factor	Replacement Cost	Present Worth
	81	PV	25	0.4776	$8,450	$4,036
		N/A	0			$0
		N/A	0			$0
		N/A	0			$0
		N/A	0			$0
		N/A	0			$0
		N/A	0			$0
		N/A	0			$0
		N/A	0			$0
		N/A	0			$0
	Totals				$8,450	
	TOTAL PRESENT WORTH OF REPLACEMENT COST					$4,036
Annual Costs	Annual Costs		% of initial cost	Present Worth Factor	Annual cost	Present Worth
	Maintenance Cost			25.7298		
	81	PV	0.0066		$56	$1,435
	0	N/A	0		$0	$0
	0	N/A	0		$0	$0
	0	N/A	0		$0	$0
	0	N/A	0		$0	$0
	0	N/A	0		$0	$0
	0	N/A	0		$0	$0
	0	N/A	0		$0	$0

	0	N/A	0		$0	$0
	0	N/A	0		$0	$0
	Electrical Energy		-5695	kwh	-$683	-$14,979
	Natural Gas			therms	$0	$0
	TOTAL PRESENT WORTH OF ANNUAL COST					-$13,544
LCC	**TOTAL PRESENT WORTH LIFE CYCLE COST**				**-$1,058**	

DISCOUNT FACTORS

Discount Factor (i) = 3%

A	B	C	D	E
	Present Worth Factor of Future Expense	Annual Payment Factor of Future Expense	Present Worth Factor of Annual Expense	Replacement Cost Factor
Year (n)	(P/F, i, n) = 1/(1+i)^n	(A/F, i, n)=i/(1+i)^n-1	(P/A, i, n)=(1+i)^n-1/(i(1+i)^n	Column C * (P/A, i, 50) = Column C * (1+i)^50-1/i(1+i)^50
0				0.0339
1	0.9709	1.0000	0.9709	25.7298
2	0.9426	0.4926	1.9135	12.6748
3	0.9151	0.3235	2.8286	8.3244
4	0.8885	0.2390	3.7171	6.1501
5	0.8626	0.1884	4.5797	4.8463
6	0.8375	0.1546	5.4172	3.9778
7	0.8131	0.1305	6.2303	3.3579
8	0.7894	0.1125	7.0197	2.8935
9	0.7664	0.0984	7.7861	2.5327
10	0.7441	0.0872	8.5302	2.2444
11	0.7224	0.0781	9.2526	2.0089
12	0.7014	0.0705	9.9540	1.8130
13	0.6810	0.0640	10.6350	1.6475
14	0.6611	0.0585	11.2961	1.5059
15	0.6419	0.0538	11.9379	1.3834
16	0.6232	0.0496	12.5611	1.2765
17	0.6050	0.0460	13.1661	1.1823
18	0.5874	0.0427	13.7535	1.0989
19	0.5703	0.0398	14.3238	1.0244
20	0.5537	0.0372	14.8775	0.9576
21	0.5375	0.0349	15.4150	0.8972
22	0.5219	0.0327	15.9369	0.8426
23	0.5067	0.0308	16.4436	0.7928
24	0.4919	0.0290	16.9355	0.7474
25	0.4776	0.0274	17.4131	0.7057
26	0.4637	0.0259	17.8768	0.6674
27	0.4502	0.0246	18.3270	0.6320
28	0.4371	0.0233	18.7641	0.5993
29	0.4243	0.0221	19.1885	0.5690
30	0.4120	0.0210	19.6004	0.5408

31	0.4000	0.0200	20.0004	0.5146
32	0.3883	0.0190	20.3888	0.4901
33	0.3770	0.0182	20.7658	0.4672
34	0.3660	0.0173	21.1318	0.4457
35	0.3554	0.0165	21.4872	0.4256
36	0.3450	0.0158	21.8323	0.4066
37	0.3350	0.0151	22.1672	0.3888
38	0.3252	0.0145	22.4925	0.3720
39	0.3158	0.0138	22.8082	0.3562
40	0.3066	0.0133	23.1148	0.3412
41	0.2976	0.0127	23.4124	0.3271
42	0.2890	0.0122	23.7014	0.3137
43	0.2805	0.0117	23.9819	0.3010
44	0.2724	0.0112	24.2543	0.2889
45	0.2644	0.0108	24.5187	0.2775
46	0.2567	0.0104	24.7754	0.2666
47	0.2493	0.0100	25.0247	0.2563
48	0.2420	0.0096	25.2667	0.2464
49	0.2350	0.0092	25.5017	0.2371
50	0.2281	0.0089	25.7298	0.2281

P Present Worth

F Future Payment

A Annual Payment

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