

**A MODEL OF NEAR-ZERO ENERGY HOME (nZEH)
USING PASSIVE DESIGN STRATEGIES AND PV
TECHNOLOGY IN HOT CLIMATES**

BY

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DEDICATION

I dedicate this thesis to region's architectural consultancies and building contractors, research groups and institutions, responsible researchers, education providers and delivery partners, forward-thinking home owners, concerned personnel, and potential employers.

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Congratulations to the Dean of Graduate Studies upon completion of my Master Thesis.

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NOMENCLATURE

ACH	:	Air Changes per Hour
ADAE	:	Active Dynamic Air Envelope
ASHRAE	:	American Society of Heating, Refrigerating and Air Conditioning Engineers
BIPV	:	Building Integrated Photovoltaic
BIPV/T	:	Building Integrated Photovoltaic / Thermal
BPS	:	Building Performance Simulation
CFL	:	Compact Fluorescent Lamp
CFM	:	Cubic Feet per Minute
COP	:	Coefficient of Performance
DHW	:	Domestic Hot Water
DXF	:	Drawing Exchange Format
GRIPV	:	Green Roof Integrated PV
GUI	:	Graphical User Interface
HDD	:	Heating Degree Days
HOMER	:	Hybrid Optimisation Model for Electric Renewables
HVAC	:	Heating, Ventilation and Air Conditioning
IAQ	:	Indoor Air Quality
IECC	:	International Energy Conservation Code
IEQ	:	Indoor Environmental Quality
IES-VE	:	Integrated Environmental Solutions - Virtual Environment
IICB	:	Integration of Intelligent Design Knowledge-Base
ISAAC	:	Institute of Applied Sustainability to the Built Environment
KACST	:	King Abdulaziz City for Science and Technology
KFUPM	:	King Fahd University of Petroleum & Minerals
LEED	:	Leadership in Energy and Environmental Design
NASA	:	National Aeronautics and Space Administration
NPV	:	Net Present Value
nZEB	:	near-Zero Energy Building
NZEB	:	Net Zero Energy Building
nZEH	:	near-Zero Energy Home
PCM	:	Phase Change Material
PMV	:	Predictive Mean Vote
PPD	:	Percentage of People Dissatisfied
PV	:	Photovoltaic
PV/T	:	Photovoltaic / Thermal
SEC	:	Saudi Electricity Company
SHGC	:	Solar Heat Gain Coefficient
TRNSYS	:	Transient Thermal Energy System Simulation
UIM	:	Usability Information Management
WWR	:	Window-to-Wall Area Ratio
ZEB	:	Zero Energy Building
ZERB	:	Zero Energy Residential Building

THESIS ABSTRACT

Full Name : SYED ASHRAF TASHRIFULLAHI

Thesis Title : A MODEL OF NEAR-ZERO ENERGY HOME (nZEH) USING PASSIVE DESIGN STRATEGIES AND PV TECHNOLOGY IN HOT CLIMATES

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Recent years have seen a drastic increase in energy use trends in Saudi Arabia. The residential building sector alone is responsible for more than half of the total energy consumed among all sectors. A research initiative was required to conserve energy in the residential sector wherever applicable. This research, therefore, focuses on the investigation of strategies in view of the concepts highlighted in the design of Zero Energy Building (ZEB).

A 4-bedroom single family faculty residence at King Fahd University of Petroleum & Minerals depicting the most common regional building design trends was considered in the study. Energy consumption of the house was monitored for three months during the summer season from July through September. A base case simulation model of the house was developed and validated using the real-time energy consumption data. Three sets of strategies namely *passive design strategies*, *representative codes and standards*, and *renewable technology* were employed in the new design of the house. Passive strategies comprised of *green roof*, *ventilated wall system*, *pitched roof*, *insulation for thermal break* and *exterior shading*. These alternatives helped reduce the annual energy consumption of the house by 17.2%. The most recent version of International Energy Conservation Code (IECC 2012) was as well incorporated along with ASHRAE Standard 62.2 for ventilation. The code and standard together helped reduce the annual energy consumption by 31.1%. Solar PV was then utilized to reduce grid utilization for the remainder of house energy loads. This strategy provided 24.7% of the total energy consumed by the house annually. A compendium of strategies showed 70.7% energy consumption reduction decreasing the energy index of the house from 162.9 kWh/m²/annum to 47.7 kWh/m²/annum. The research does have some limitations in its implementation but represents a first initiative in Saudi Arabia. The ZEB concepts and strategies utilized demonstrate socially responsible approach in achieving near-zero energy performance of an existing house.

THESIS ABSTRACT ARABIC

ملخص الرسالة

الاسم : سيد أشرف تشريف الله
عنوان الرسالة : نموذج لمسكن ذو طاقة استهلاكية تقترب من الصفر باستخدام استراتيجيات التصميم التي لا تستهلك طاقة (الاستراتيجيات السلبية) والخلايا الكهروضوئية في بيئة المناخ الحار
التخصص : الهندسة المعمارية
تاريخ الدرجة : ابريل 2014م

شهدت السنوات الأخيرة زيادة عظيمة في التوجه لاستخدام الطاقة في المملكة العربية السعودية. وقد أصبح القطاع السكني مسؤولاً عما يزيد عن نصف استهلاك الطاقة في العام لجميع القطاعات. ولذلك استدعت الحاجة الى مبادرة لتوفير استخدام الطاقة في هذا القطاع بوسائل عديدة. ومن هذا المنطلق فإن هذه الدراسة تركز على التحقيق والبحث في الاستراتيجيات الممكنة في ضوء المفاهيم التي يشار إليها بتصميم مبنى ذو اجمالي طاقة تقترب من الصفر.

تم دراسة مبنى سكني لعائلة واحدة من مباني الأساتذة في جامعة الملك فهد للبترول والمعادن من أجل إنجاز هذا البحث، و يتكون المسكن المستقل (فيلا) من دورين بها أربع غرف نوم، يحاكي تصاميمها شريحة من المباني السكنية المستقلة الشائعة في المنطقة. تم متابعة وقياس استهلاك الطاقة لهذا المسكن على مدى ثلاثة أشهر خلال فصل الصيف من شهر يوليو إلى شهر أغسطس. كما تم تطوير نموذج محاكاة للحالة المبدئية للمسكن وتم التحقق من هذا النموذج باستخدام بيانات استهلاك الطاقة الفعلية له. ثم توظيف ثلاث مجموعات من الاستراتيجيات في تحسين الأداء الحراري للمسكن هي: أساليب التصميم السلبية، الكودات (النظم) القياسية ذات العلاقة، وتكنولوجيا الطاقة المتجددة. تتألف استراتيجيات الطاقة السلبية من الأسقف الخضراء، أنظمة الجدران المغلقة ذات التهوية، والأسقف المائلة، والعزل الحراري للفواصل، والتغطيات الخارجية. وقد ساعدت هذه البدائل على تقليل الاستهلاك السنوي للطاقة للمبنى بمقدار جنبا إلى جنب مع المعايير (IECC 2012) 17.2%. وقد استخدمت النسخة الاحدث من الكود الدولي لحفظ الطاقة للتهوية. وقد ساعد استخدام 62.2 (ASHRAE) القياسية للجمعية الأمريكية لمهندسي التدفئة والتبريد وتكييف الهواء هذه النظم والمعايير القياسية على تقليل الاستهلاك السنوي للطاقة للمبنى بمقدار 31.1%. كما تم أيضا استغلال الخلايا الكهروضوئية للحد من استخدام الكهرباء من الشبكة العامة لتغطية أحمال الطاقة للمسكن. وقدمت هذه التقنيّة 24.7% من الاجمالي السنوي للطاقة المستهلكة للمسكن. وكخلاصة شاملة، فإن استخدام التقنيات الأنف ذكرها أظهر توفيراً باستهلاك الطاقة بمقدار 70.7% وبما يقلل مؤشر الطاقة للمنزل من 162.9 (كيلوواط ساعة\ متر² سنة) إلى 47.7 (كيلوواط ساعة\ متر² سنة). ورغم وجود العديد من المحررات في تطبيق البحث ولكنه يمثل خطوة ومبادرة أولى في المملكة العربية السعودية. ويبرهن مفهوم واستراتيجيات المبنى ذو الطاقة الاجمالية التي تقترب من الصفر على نهج المسؤولية الاجتماعية في تحقيق أداء استهلاكي للطاقة يقترب من الصفر لمسكن قائم.

CHAPTER 1

INTRODUCTION

1.1 Background

Sustainability is a term that describes the exploitation of those resources that are ongoing in nature. Energy being the ability of a physical system to do work is always continuing in nature and has become the most basic necessity of life for human beings. Energy consumption now-a-days is greatly increased in almost all sectors with the building industry accounting the most. As per US Energy Information Administration in their Annual Energy Review for the year 2010, the building industry accounts for 42% energy end use of total consumption of which the residential sector accounts for 23% (U.S. Energy Information Administration, 2011). If the statistics of the Saudi Electricity Company (SEC) for the year 2010 are compared, the building industry in Saudi Arabia accounts for approximately 76% out of which the residential sector accounts for about 51%. Similar observation was witnessed for the year 2011 by the SEC as shown in **Figure 1.1**. Further, the Saudi Arabian residential building sector in the year 2012, as reported by the SEC, marked 10% increase in energy end-use of the total energy consumed in comparison to the year 2011. Moreover, the energy demands mostly depend on conventional energy sources that are non-renewable. Thus, making the energy available in the form of electricity wherever and whenever needed, especially in the residential sector, has become a growing challenge in the Kingdom. Hence, meeting these demands in a sustainable and socially responsible ways is among the best of approaches that may take

into consideration any of the available renewable energy sources and combinations thereof. One such approach is the application of the concept of near-Zero Energy Homes (nZEH) that utilize both passive design strategies and PV technology in home design.

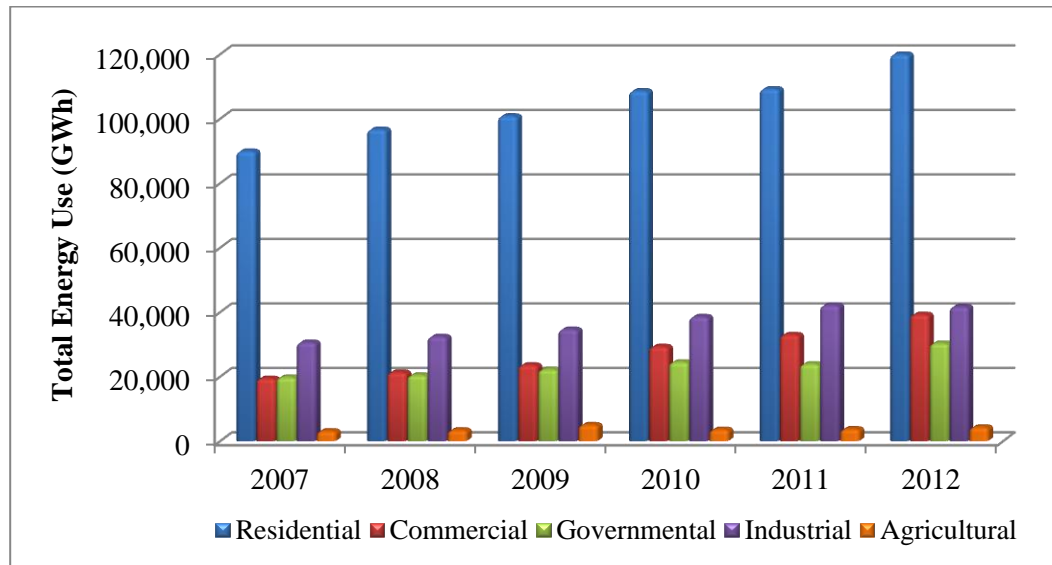


Figure 1.1: Energy End-Use History of the Saudi Arabian Building Industry (Saudi Electricity Company)

U.S. Department of Energy defines a Zero Energy Building (ZEB) as a building with greatly reduced energy needs using renewable technologies being able to supply these needs. It produces as much energy at the site as it uses yearly (Torcellini et al., 2006). It is a building that uses traditional energy sources depending on either the unavailability of the on-site energy generation technologies or when the on-site energy generation technologies do not meet the loads of the building. As described by International Energy Agency (Laustsen, 2008), a ZEB is a traditional building housed with large photo collectors and photo voltage systems. Although ZEB is not easy to achieve; a step could be taken forward to investigate the viability of near zero energy mark. This concept describes a ZEB in a slightly different way as “near-Zero Energy Building” (nZEB) and when seen from the view point of a single family dwelling is called as “near-Zero Energy

Home” (nZEH). Such home design could be achieved by utilizing the passive strategies which is considered as the first step to a sustainable home. The next step would be to take advantage of the on-site energy generation technology. This approach not only reduces the load of the building but also offsets the electric energy available from the grid thereby approaching or nearing to the zero energy mark.

Passive design, as mentioned earlier, is the first and foremost step to a sustainable building. It utilizes solar energy to heat or cool the building or a part of the building and reduces corresponding loads. It takes into consideration various strategies in building design, depending upon climatic variations, ranging from the most typical ones to the most innovative. Passive design is understood as an approach that eliminates the need for active mechanical systems while maintaining or improving occupant comfort (Passive Design Toolkit, 2009). However, this could not be easily achieved for hot-humid climates. The dependency of the active systems could only be reduced. This is possible with the help of passive design elements. As cooling is the major concern, the elements that contribute to passive cooling include fixed/operable external shading, thermal mass, low window-wall area ratio, stacked windows, etc and from a different perspective are called as principles of passive solar design (Johnston and Gibson, 2010). Passive design strategies for homes to achieve near Zero Energy mark from the view point of building envelope include orientation, high R-value wall assemblies, high R-value roof assemblies, window-wall ratio, Low-e glazing, building massing, shading, etc. From the perspective of active systems in buildings, design strategies include lighting, daylighting and HVAC. Most proper design strategies could be utilized as part of performance based analyses with the help of state-of-the-art tool(s).

According to Johnston, the first pre-requisite of zero energy building (ZEB) is designing a house that responds to its site and climate. This concept is no different than the one described earlier, i.e. passive design. The next step would be to find ways to meet the reduced loads. Saleh and Taleb explored renewable energy options in Saudi Arabia and studied the viability of solar PV in the residential sector (Al-Saleh and Taleb 2009). Said and his colleagues addressed the potentials of renewable energy applications in Saudi Arabia by considering wind and PV (Said et al., 2004). The renewable energy options and potentials could be taken further by considering PV technology for implementation in Zero Energy Homes to meet reduced energy demands and approach to zero energy.

1.2 Statement of the Research Problem

The residential buildings in Saudi Arabia consume large amounts of energy of about 50% of the total energy consumed (Saudi Electricity Company, 2012) and mostly depend on the availability of electricity from the grid. Out of the total energy available, about two-thirds of energy is lost in electricity production. The primary source of electricity in the Kingdom being non-renewable oil reserves led to the identification of a research component to conserve energy in the residential sector. Hence, the research will focus on passive design techniques for energy demand reduction followed by utilization of solar PV technology to meet those reduced demands.

1.3 Significance of the Research

The research will propose design and construction strategies, and guides to conserve energy in the residential sector relevant to new single-family detached dwellings built in hot climates. It will focus on the development of the best overall near-Zero Energy Building reference model of a single-family detached home meeting a part of the electric

load by sustainable and clean energy. The study may also provide valuable contributions to those concerned in revising the relevant Saudi Building Code in near future.

1.4 Objective

The main objective of the research is to investigate the most proper passive design strategies integrated with solar PV technology to achieve near-Zero Energy Home design in Saudi Arabia.

1.5 Scope and Limitations

Zero Energy Building (ZEB) is a sustainable and socially responsible approach to building design. The scope of this research is to utilize and investigate the passive design strategies in integration with PV technology to achieve nZEH design in Saudi Arabia. Passive design of buildings is an approach that improves the energy performance and when used in conjunction with building integrated solar systems meets the reduced energy demands thus approaching near zero energy. This methodology gives the feasibility of endless design ideas leading to improvement in design where passive meets active. As a result, all possible and potential strategies and systems work in tandem with each other in one single design of innovation. The thesis research work is limited to hot-humid climates as characterised by the weather in Dhahran. The major limitation of this research is the proper integration of PV with the roof structure. Integration of a physical / thermodynamic system with the other takes into account the heat exchange between them, which is highly likely to be absent in this simulation based research as it depends on the availability and capability of state-of-the-art software tool(s). Thus, the heat exchange between the PV system, the building envelope and the resulting impact could not be

modelled, and both the systems can only be theoretically assumed to be working in tandem as one.

1.6 Research Methodology

The research methodology set to achieve the aforementioned objective is divided into various phases as discussed below:

Phase-1: Literature Review

- Studies related to Zero Energy Building (ZEB) design highlighting the concepts and requirements involved.
- Investigation of passive design strategies and their impact on energy use.
- PV technology integration with building envelope for electricity generation as a means to meet the reduced energy demands.
- Review of state-of-the-art Building Performance Simulation (BPS) tools for ZEB design. Selecting appropriate tool capable of modelling selective passive strategies and capable of accounting for energy end-use.
- Representative code and standards for Zero Energy Building design for homes.

Phase-2: Formulation of Base Model and Substantiation

- Selection of an already existing building that best describes traditional but most recent design approach of a single family detached home in Saudi Arabia.
- Collection of required building characteristics from relevant organizational sources and identification of related base case model development parameters.
- Substantiation of results of the base case model by real-time performance monitoring of the house. This includes a review of, simulation model relevant, building services conglomerate of the house by installing energy monitors for the core summer period to identify energy flows and end-use patterns.
- Performing the required and necessary simulation runs for verification of base case model.

Phase-3: Investigation and Design Analysis

- Investigation of selected passive strategies. Implementation of each in the base case for performance evaluation individually.
- Identification of most proper strategies and subsequent implementation of all for performance evaluation.
- Thermal comfort analysis and evaluation of the strategies implemented.
- Design of PV system to meet certain threshold of remaining load requirements based on building model simulation results to achieve much needed energy performance index for near-zero energy performance.

Phase-4: Results Analysis and Discussion

- Discussion of base case house model in terms of its energy performance and thermal comfort.
- Assessment of impact of each strategy on energy performance of the house.
- Review of conglomerate of strategies on energy performance and thermal comfort.
- Comparison between energy performance and thermal comfort criteria of base case and nZEB house models.
- Simple techno-economic analysis of solar PV system for payback estimation.

Phase-5: Conclusions & Recommendations

- Concluding remarks upon achieving near-zero energy performance, and explanatory inputs for a step toward zero energy performance.
- Recommendations with regard to the case study and strategies employed, and proposals for future work.

The research methodology is as well depicted in **Figure 1.2** as follows:

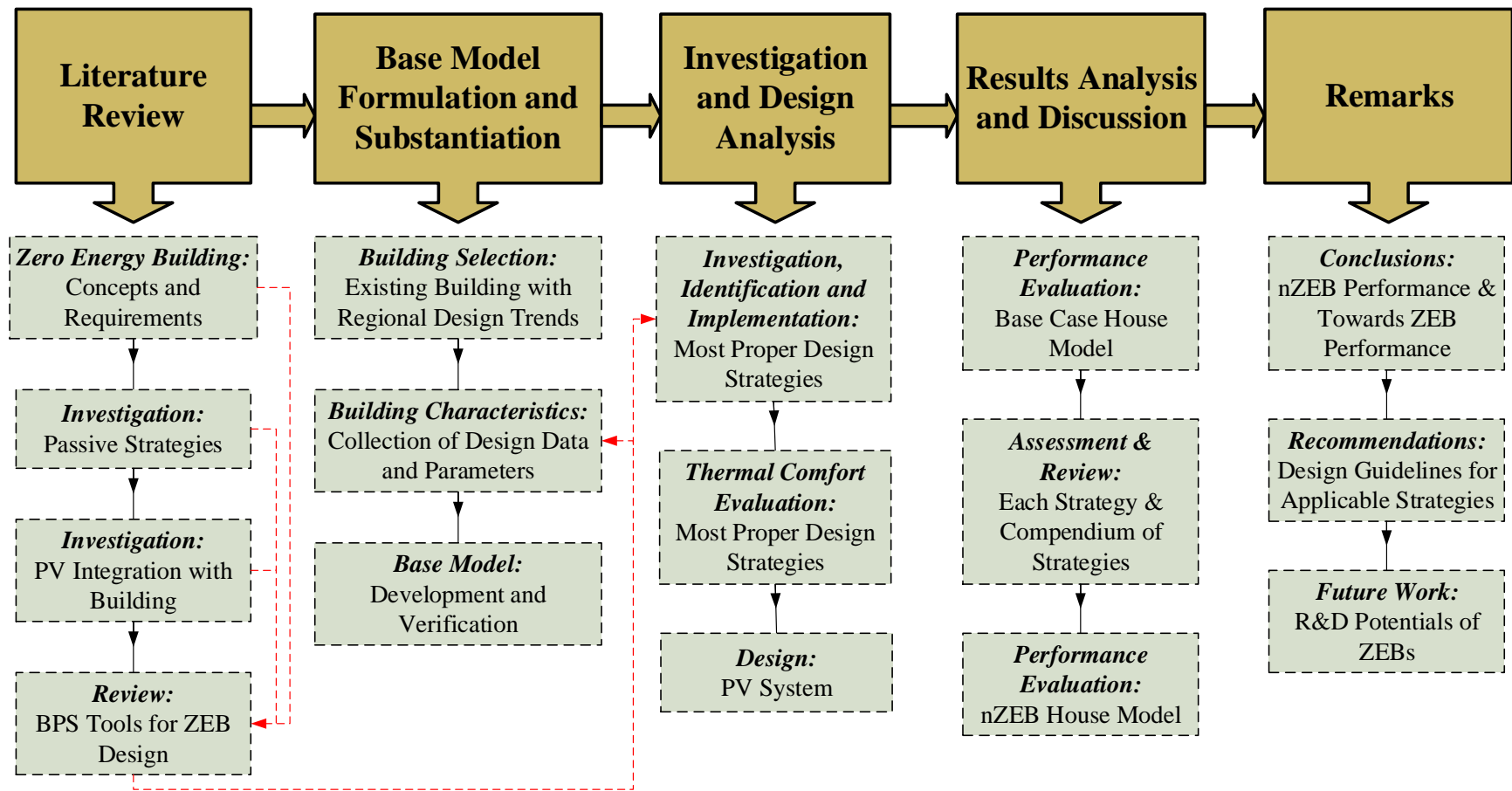


Figure 1.2: Research Methodology

CHAPTER 2

LITERATURE REVIEW

The thesis literature focuses on the studies carried out by researchers on Zero Energy Buildings (ZEB) and their design, and highlights the concepts and requirements involved. This is followed by the description of passive design strategies that are to be addressed as the first step towards zero energy or near-zero energy targets. The thesis literature also enlightens its readers with various passive strategies that were of interest to this research. As increase in energy performance of a building is evident upon utilizing various passive design strategies, the literature also includes recent research endeavours and advancements in PV (PV) applications to buildings. The use of Building Performance Simulation (BPS) programs for ZEB analysis is studied as well. Highlights in this area include comparison of a number of BPS tools from the view point of their usefulness and applicability for passive design strategies and renewable technologies that help achieve the zero energy status.

2.1 Zero Energy Building (ZEB)

The Building Technologies Program of the U.S. Department of Energy (DOE) defines a Zero Energy Building (ZEB) as a building with greatly reduced energy needs using renewable technologies being able to supply these needs. As described by International Energy Agency (Laustsen, 2008), a ZEB is a traditional building housed with large photo collectors and photo-voltage systems. Iqbal describes a ZEH (Iqbal, 2004) as follows: *Zero energy home is the term used for a home that optimally combines commercially*

available renewable energy technology with the state of the art energy efficiency construction techniques. A research endeavour described a framework that provided a consistent definition of Net Zero Energy Building (NZEB) depending upon a country's political targets and specific conditions (Sartori et al., 2012). Also highlighted was an overview of the terminology and the balance concept of a NZEB highlighting various energy and load matching indicators. Identified was the import / export balance that talks about the amount of energy imported or exported between the building and smart grid and load / generation balance that focuses on the total load of the building in comparison to its generation. In defining a zero energy solar home, a study gave emphasis on the use of solar thermal and solar PV technologies in meeting the energy equivalent to the home's yearly load (Charron and Athienitis, 2006). But lacking was a common definition and understanding of the terms "zero energy" which finally led to four different conceptual definitions of zero energy, i.e. what measurable quantity should be zero (Torcellini et al., 2006). These included *net-zero site energy*, *net-zero source energy*, *net-zero energy costs* and *net-zero energy emissions*. Following are the definitions of the aforementioned technical terms:

- ***Net-Zero Site Energy:*** *A site ZEB produces as much energy as it uses in a year, when accounted for at the site.*
- ***Net-Zero Source Energy:*** *A source ZEB produces at least as much energy as it uses in a year, when accounted for at the source. Source energy refers to the primary energy used to generate and deliver the energy to the site.*
- ***Net-Zero Energy Costs:*** *In a cost ZEB, the amount of money the utility pays the building owner for the energy the building exports to the grid is at least equal to*

the amount the owner pays the utility for the energy services and energy used over the year.

- ***Net-Zero Energy Emissions:*** *A net-zero emissions building produces at least as much emissions-free renewable energy as it uses from emissions-producing energy sources.*

The impact of the design is usually dependent on the definition (Torcellini et al., 2006), i.e. it is dependent on how one perceives the terms “zero energy”. Thus, the main aim of citing the definitions was to identify the right context in which the research was to be conducted. Hence, interest was shown in the definition of “net-zero site energy”. The term “net” is used for net metering where the difference between inflows and outflows of energy through the smart grid is eventually zero. However, the concept of research here was to focus on “zero site energy” eliminating the grid system which in other words is called as site zero energy building or simply Zero Energy Building (ZEB). This when seen from the view point of a single family dwelling is called as Zero Energy Home (ZEH). A technical report later presented a classification system for NZEBs depending on the type of renewable used by the building (Pless and Torcellini, 2010). The classification ranges from “ZEB A” through “ZEB D” with ZEB A ranked as the best, ZEB B & ZEB C ranked as better and ZEB D ranked as good energy supply options for the building. To be more precise, the center of attention to the thesis is ZEB A which utilizes renewable sources within the footprint of the building.

As ZEB/ZEH needs to produce energy for sustenance, this energy comes from various renewable technologies. The amount of energy produced is limited depending on the technology selected and climatic variations. Thus, the energy demand of the building

should be less such that the renewable is capable of supplying it. This could be achieved by improving the energy efficiency of the building. The first prerequisite of a ZEB is designing a house that responds to its site and climate (Johnston and Gibson, 2010). This concept is known as passive design. They discussed various principles of passive solar design for homes to achieve energy efficiency. Some of these principles are orientation, super-insulating the envelope, thermal massing and shading. Passive solar balances all components that make it work year round. Once energy efficiency is ensured, the next step, as mentioned by Johnston and Gibson, is to take advantage of renewable technologies such as solar PV, wind, geothermal, etc for energy production. The most common and attractive option for homes would be solar PV for a variety of reasons and is typically a part of zero/net-zero strategy. Another option that could be used in conjunction with PV is solar thermal. Together PV and thermal systems are known as PV/T system; PV for producing electricity and T for let us say Domestic Hot Water (DHW) application. A number of studies could be cited on *passive solar design concepts* and use of *renewable(s)* to achieve zero/net-zero energy status.

Insights on the definition and verification of energy indices of NZEB were recently presented in a technical document (Norris and Lollini, 2013). Provided was a standard measurement and verification process as a protocol which must be undertaken at various monitoring phases for energy balance verification and IEQ assessment. The protocol supports the planning, execution and post-processing of energy and IEQ data for NZEB monitoring. The authors believe that physical and balance boundaries are equally important (building, measurement and verification) when it comes to defining a NZEB.

The physical boundary comprises the building itself and the balance boundary is the system(s) included in the calculation, i.e. heating, cooling, ventilation, etc.

A study described the NZEB design concept as a progression from passive design (Kolokotsa et al., 2011). A number of innovative technologies have come into existence and improved overtime. All these held great potential to improve energy performance and thermal comfort in buildings through improvements in building envelope (thermal insulation, building massing and phase change materials), innovative shading devices, highly efficient HVAC systems, energy management systems, etc. Moving a step further was the useful resource of renewable technologies in order to balance the energy demands. In relation to the above mentioned design procedure of passive techniques followed by renewable technologies for ZEB, a research work was carried out in the United Kingdom on zero energy house design (Wang et al., 2009). Discussed and compared were possible ZEB design solutions using EnergyPlus and TRNSYS 16 to provide optimal design strategies for typical homes in the UK. The use of more than one software tool here in this study was evident because to successfully design a ZEB one needs to identify passive strategies for energy efficiency followed by the identification of appropriate renewable(s) to meet the remaining demands. TRNSYS is known for its renewable systems' simulation capabilities and EnergyPlus for analyzing passive architectural building systems. Wang et al. used EnergyPlus for façade designing, building orientation and window analysis. TRNSYS was used to assess the design with PV, wind, solar hot water and efficient heating systems applications. As a result of the analyses, as mentioned earlier, they came up with optimal design strategies. The annual electricity generation using both PV and wind turbine exceeded by a magnitude of 1297

kWh than the annual electricity consumption of lighting, appliances, DHW and floor heating system. The study aimed and identified theoretically zero energy house design in the UK. The optimum design strategies proposed by the researchers included a WWR of 0.4 on south façade, 0.1 or less on east, west and north facades. The study also mentioned an optimum solar panel area of 5 m² at a mass flow rate of 20 kg/hr to meet the solar domestic hot water DHW application of 98 L/day. Finally a three step whole design process was summarized: local climate data analysis to promote zero energy houses, passive design to reduce loads, and renewable technologies to meet the reduced loads.

An exhaustive technical review of building envelope components was carried out (Sadineni et al., 2011). The idea here was to significantly reduce the energy consumption with the help of energy efficient strategies. To start on with the task, the authors discussed a variety of energy efficient walls in the paper. These included Trombe walls, glazed walls and ventilated walls. Also discussed were different fenestration technologies with aerogel, vacuum glazing and frames. In other classification of building envelope components, discussed were advancements in green roofs, PV roofs, etc. Thermal insulation, thermal mass, phase change materials, air tightness and infiltration were as well given a worthy consideration. Incorporating all of the aforementioned approaches into the building provides a holistic energy efficient building design that could reduce energy consumption and cut down the respective costs. According to the authors, this approach is a passive design approach and elements mentioned are passive strategies that could be utilized based on climatic consideration. Highlights on how building energy modelling could be helpful were also provided.

A team of architect, structural and MEP engineers, and building automation personnel worked on the design of a unique residential building project called the Leaf House (Morodo and Cesarini, 2013). A systematic design approach was followed to bring the Leaf House project toward Net Zero Energy target. This included the integration of building envelope systems, energy saving techniques, renewable energy systems, and automation systems. A research initiative on building energy modelling efforts detailed net-zero energy residence by combining passive and active strategies in six different climates in three simple steps (Stephens, 2011). These include *passive low-energy design strategies and energy efficiency measures, selection of a combination of strategies, and pairing of predicted energy consumption output with output of a PV system*. After performing the analysis and exploring the results on an annual, monthly and hourly basis, the low-energy design strategies estimated a reduction of annual energy consumption of 19-30% compared to a baseline code-compliant home. The amount of energy the PV system produced was found enough to cover the hourly demand in less than two-thirds of a typical year. The remaining one-third of the year witnessed exceeded energy demand from the same system. The capacity of smallest PV system was found to be 10 kW and the largest as 23 kW. The research focused on six different locations in the United States and suffered a major disadvantage. The PV system had to be greatly oversized in order to meet the annual energy demand of the building in the periods when the sun did not shine. However, no cost analysis was shown in the study. These studies show how the craze of zero energy and low energy buildings has greatly increased. Today one can find a number of relevant studies in various parts of the world. Recent study carried out in Sweden focused on the investigation of energy performance of newly built low-energy buildings (Molin et al., 2011). Like other countries, energy consumption in buildings in Sweden

represents large part of the energy end use. Investigated was the performance of passive homes to meet the European goals. A total of nine homes were built with an annual heating demand of 21 kWh/m². Building Energy Simulation (BES) was utilized in the evaluation of homes. The results of the parametric analyses carried out indicate various changes in the envelope of the buildings. However, the overall energy performance of these newly built homes was satisfactory and met the expected design value of 21kWh/m².

In a recent study, interest was shown in the energy balance using green roof integrated with PV systems (GRIPV) (Witmer and Brownson, 2011). The green roof is a passive strategy which is the first step towards ZEB. The strategy reduces solar heat gains from the roof of the building thereby reducing the cooling energy. The use of PV system helps offset the reduced demand of the building. Most importantly, the performance of a PV system deteriorates as it gets heated. The green roof helps remove heat from the PV panels besides reducing heat gains. Research on the use of phase change materials as a passive strategy to store energy and to increase the thermal mass of the building for efficient use of energy was carried out (Behzadi and Farid, 2010). This led to reductions in daily fluctuations of indoor air temperatures resulting in maintaining desired comfort level for longer period of time.

Cited in a white paper titled “Zero and Net-Zero Energy Buildings + Homes” on Green Building Movement was William Maclay’s, founder and president of Maclay Architects, step-by-step design guide to Net-Zero Energy Building (NZEB). Seven steps in the design process were proposed that included strategies other than the traditional ones as described and discussed above. The first step to NZEB is to employ a highly collaborative and

integrated design process. Steps two and three, as discussed earlier, are passive in nature and talk about the orientation of the building and super-insulation of the building envelope respectively. This is followed by optimal energy generation renewable system depending on the site and climate. The next step is to specify mechanical systems that support net-zero goals. No matter how many systems are used to successfully design a NZEB, in the sixth step one must ensure the systems' proper operation by setting up a monitoring system. Lastly, a periodical review of energy performance of the building should be carried out in step seven to identify problems and to educate the ones responsible in monitoring and running the facility.

2.2 Design Strategies for ZEB

A study presented a work on Net Zero Energy Schools that explained the viability of the most typical design strategies to achieve Net Zero Energy status (Hutton, 2012). Main area of focus was the Net Zero Pyramid that incorporates the most typical design strategies to achieve net zero energy status. The hierarchy of these strategies based on their initial importance is as follows: *Building Envelope/Orientation*, *Daylighting/Electric Lighting*, *HVAC* and lastly *Renewable Energy*. Till now it was seen from various sources in literature that in order to design a ZEB a common strategy followed by almost every source was to utilize passive strategies and then use renewable technologies. But these two together form only a part of the most typical design strategies in the energy pyramid as shown in **Figure 2.1**.

The difference between passive strategies and typical design strategies is that where passive strategies are thought of as shading, WWR, green roof, etc., typical design

strategy is thought of as an inclusion of passive strategies, use of energy efficient lighting and HVAC, and renewable technologies.

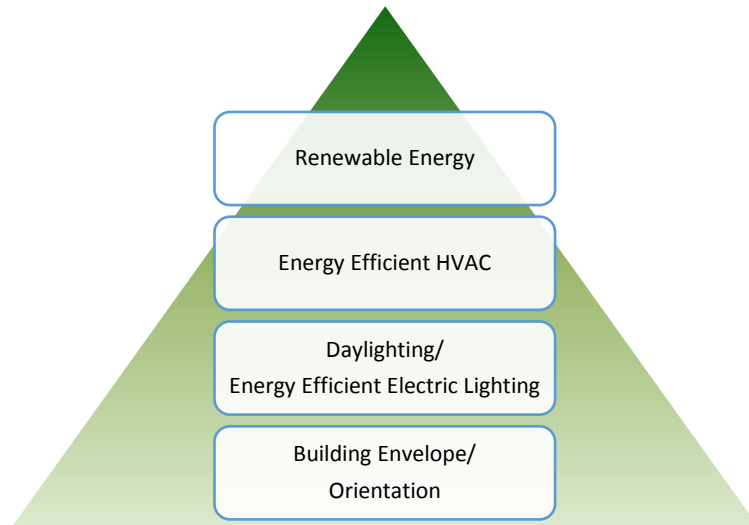


Figure 2.1: Net Zero Pyramid (Hutton, 2012)

Passive Design is defined as a method to minimize the energy consumption and improve thermal comfort by using the architecture of the building (Passive Design Toolkit, 2009). It is understood as an approach that eliminates the need for active mechanical systems while maintaining or improving occupant comfort. The toolkit comprises of various passive design strategies, each of which is made of several passive design elements. The strategies are as follows: *passive heating*, *passive ventilation*, *passive cooling* and *daylighting*.

2.2.1 Passive Heating

It is a strategy to harness the heat from the sun with the help of building design. This increases free thermal energy in the form of heat gains into the building. It comprises of a number of design elements. These include *orientation*, *building shape*, *buffer spaces* and *double facades*, *space planning*, *high performance windows*, *mixed-mode heat recovery*

ventilation, low and high WWR, operable external shading, high performance insulation, thermal mass and minimized infiltration.

2.2.2 Passive Ventilation

The difference between indoor and outdoor temperatures causes pressure differentials and negatively impacts a building unless it is properly ventilated. Ventilation could be either active or passive in nature. Passive ventilation introduces naturally occurring air flow patterns inside the building and has three common approaches. These are *single sided ventilation, cross ventilation* and *stack effect*. The applicability of each differs from the other based on *type of building, its configuration, building shape, space planning, orientation, operable windows, etc.*

2.2.3 Passive Cooling

Planning for passive heating is simpler than passive cooling. It requires careful design in order to avoid overheating of the building from heat gains. Passive cooling minimizes solar heat gains and can even remove internal heat gains thereby avoiding the building from overheating. Elements in this category of passive strategy include *fixed/operable external shading, thermal mass, low WWR, passive ventilation, nocturnal cooling, stacked windows, passive evaporative cooling* and *earth tempering ducts*. Each passive cooling element has specific advantages and disadvantages depending on the climate. Some of them cannot be used for hot-humid climates as humidity comes into picture. A broader understanding is required to select a passive cooling element for implementation in hot-humid climates.

2.2.4 Daylighting

Daylighting is one of the strategies to reduce the electric lighting load and space cooling load. It controls the admission of natural light into the building. It is usually achieved by externally shading a portion of the building based on factors such as orientation and geographic location. This allows the daylighting strategy to control the admission of natural light by maximizing the use of diffused daylight throughout the interior of a building. The features contributing to daylighting include *space planning, high ceiling paired with tall windows, WWR, window placement, interior surface colours and finishes and skylights and light tubes*.

The above mentioned strategies are considered as the best practices that describe efficient utilization of solar energy for reduced house loads. Then come various design strategies that incorporate *orientation, interior layout, insulation, windows, lighting, ventilation, thermal mass and density*. Each one is briefly discussed as follows:

2.2.5 Orientation

Orientation always plays a crucial role in building design. It helps gain access to effective utilization of solar energy depending on geographic coordinates and earth's axis. As sun rises in the east and sets in the west another worthy consideration in this regard is the alignment of the home along the east-west axis. The conductive heat flow must be restricted in order to improve the thermal performance of the envelope. This could be achieved by considering the form factor of the building which in other words is called as the building shape. Shapes that are complex in nature leak energy by exposing more surface area of the envelope to the exterior environment. Thus, a compact design of the

envelope should be utilized to minimize surface area thereby reducing heat gain or heat loss potential. The compactness should be as close to square as possible to minimize corners. As window-to-wall area ratio (WWR) is studied to design a window for a particular orientation, the floor-to-envelope area ratio should be studied to maximize floor area in relation to envelope area.

An ideal elevation must be selected to incorporate the windows. East and west elevations have large values for heat gains compared to south. Heat transfer is at its peak when the angle of incidence of solar radiation is at its minimum. An advantage with the south elevation is that windows on south do not experience minimum angle even when sun rises or sets compared to its east and west elevation counterparts. This makes the south elevation an attractive choice. For climates witnessed in Saudi Arabia, solar gain is a big concern and strategies need to be employed to reduce it. The southern elevation can be utilized by increasing WWR area ratio compared to east and west elevations. In addition to this, appropriate external shading devices should be designed that help reduce solar gain in summer and allow direct solar gain in winter when the sun is low. The eastern and western elevations can have minimum WWR to reduce solar gain in summer. The north elevation does not experience direct solar gains and can be utilized for daylighting.

2.2.6 Interior Layout

Interior layout facilitates strategies such as thermal mass, lighting and ventilation depending on the orientation and elevation of the building. It talks about ideally allocating places such as kitchen, living room, bed rooms and mechanical systems in a home.

2.2.7 Thermal Insulation

Insulation is considered as the most important determinant of both energy savings and indoor thermal comfort. When installed properly within wall and roof assemblies, reduces heat transfer and thermal bridges. Selection of appropriate insulating material for application takes into account *climate of interest, environmental impact, IAQ impact, level of thermal resistance, its benefits other than insulating, cost-effectiveness, specific heat capacity, fire resistance, noise reduction, density, etc.* The insulation is effective only when the structure of the building is air tight and without any leakages. More importantly, the insulation itself should not have cuts in between. Hence, a continuous insulation is usually preferred. If the insulation is not continuous, it entails thermal bridging thereby allowing heat to transfer inside the envelope. As the selection of insulation is climate specific, consideration must be given to the placement of insulation where water vapour comes into picture based on the thermal properties of moist air.

2.2.8 Windows

A home without windows is impractical for a variety of reasons. A window harnesses the power of the sun by allowing passive solar gain during winter. Effective design of windows takes into account *daylighting, ventilation, views, amount of heat gain or loss through a window, cost-effectiveness of high performance systems, overhangs, landscaping, etc.* Following considerations should be given in designing windows: *thermal quality & style of window, location & size and shading.* The quality of window is determined by the thermal quality of glass and frame and solar heat gain coefficient (SHGC) of the glass. The number of glasses used in one window frame account for the

performance of a window. Minimizing the number of windows such that they do not exceed 2/3 of the envelope and avoiding over-glazing are crucial in reducing solar gains.

2.2.9 Lighting

Design with climate is always beneficial. Orientation as the first step in the design strategy has been helpful in many areas including lighting. An appropriate building layout and orientation reduces the need for electric lighting and improves occupant comfort. A good lighting design is the one that provides balanced lighting levels. This could be achieved with the help of multiple window orientations. Lighting design considers the following: *primary function of the space, type of lighting required, occupancy and style and placement of windows with respect to the path of the sun*. There cannot be a house without artificial lighting these days. The use of compact fluorescent lamps (CFLs), more energy efficient light bulbs, automation techniques, smart technologies, dimmer switches and motion detectors help to reduce lighting energy consumption. Another strategy that minimizes the use of artificial is paint. It makes the spaces look bright and reduces heat gained into the space as a result of artificial lighting.

2.2.10 Ventilation

The difference between indoor and outdoor temperatures causes pressure differentials and negatively impacts a building unless it is properly ventilated. Ventilation could be either active or passive in nature. Passive ventilation introduces naturally occurring air flow patterns inside the building and has three common approaches. The placement of windows is crucial to make a design impact for ventilation. They should be placed such that stack effect or cross-ventilation is possibly achieved. The type and style of window selected also affects the ventilating air. Following should be given importance in

designing a home for ventilation: *patterns of prevailing winds, wind flow pattern around the building and fenestration orientation to direct wind as required.*

2.2.11 Thermal Mass

The concept behind thermal mass is the ability of the mass of the envelope to absorb heat and release the same as required. This is called as thermal lag and is achieved as a result of the time taken by a material to store heat and later release it. The placement of thermal mass varies with orientation for different climates. For example, mass located on south is most efficient for heating application in some climates. Location of thermal mass is best at the ground floor as it absorbs and releases heat easily. Like thermal mass, now-a-days increased importance is being given to phase change materials as well.

Another strategy used to design net-zero compliant buildings is explained in two-step net-zero process diagram as shown in **Figure 2.2** (Chalfoun et al., 2011). The first step related to Pre Net-Zero status incorporates prescriptive and performance paths to qualify the building for the set target. The prescriptive path here is based on relevant building code where pre-defined high performance savings measures are selected under various categories. The performance path is based on the use of appropriate BPS tool for design process evaluation.

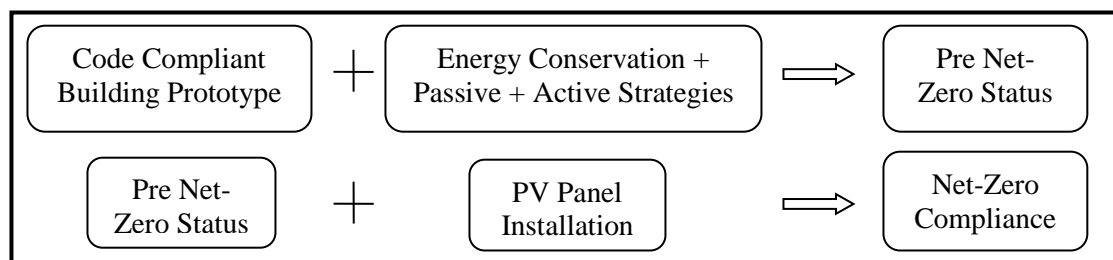


Figure 2.2: Net-Zero Process Diagram (Chalfoun et al., 2011)

The second step is related to the Net-Zero energy status where Pre Net-Zero status in conjunction with appropriately sized PV systems leads to Net-Zero compliance. The authors have found this strategic process to be the most flexible and innovative thereby allowing design excellence with high performance.

The aforementioned strategies proposed in the net zero pyramid, passive design toolkit, and net-zero process diagram are practices that should be followed to design a home that consumes less energy and produces as much as it consumes. In relation to one of these, a study provided an insight on the function of form factor / building shape on energy (Straube, 2012). Highlighted were two aspects related to building shape and energy consumption. The first one, i.e. compactness, defined as volume-to-surface area ratio can be seen in **Figure 2.3**. This is used in Europe and according to a German code high R-values are prescribed for buildings that are less compact.

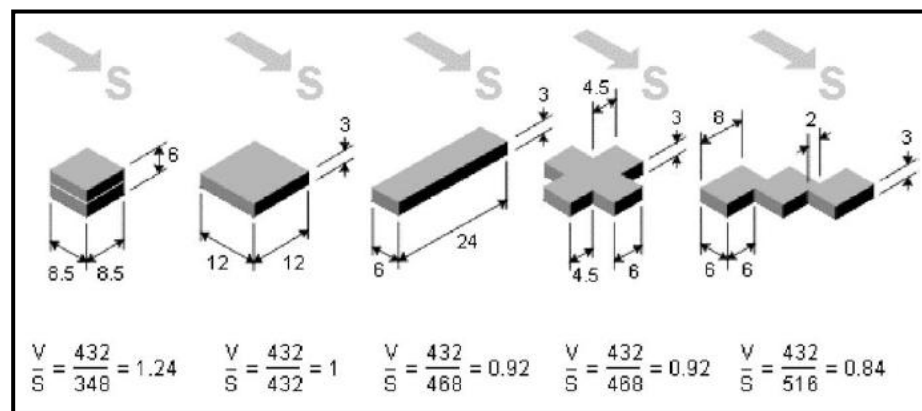


Figure 2.3: Best to Worst Building Envelope Form Factor Based on Compactness (Gratia and De Herde, 2003)

The graphic above explains that if the volume of a building is more than its surface area, inclusive of walls and roof, then the building is energy efficient. Most of the highly efficient homes have compactness of around 1 or higher. Another aspect that is for

commercial buildings is the floor-to-envelope area ratio. If the floor area is more when compared to the envelope area then the building's shape is considered to be compact as can be seen in **Figure 2.4**. The impact of the form factor on energy consumption is less for larger buildings than smaller buildings such as homes for a given floor area.

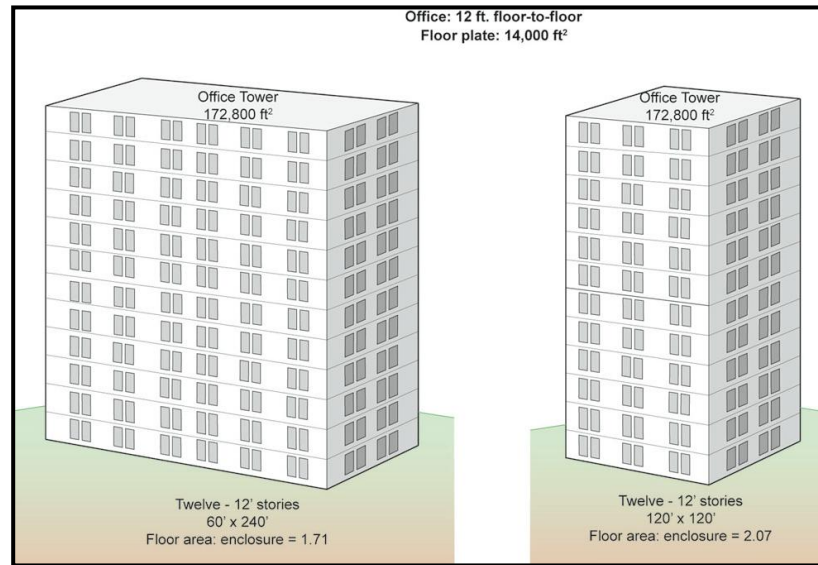


Figure 2.4: Impact of Form on Floor-To-Envelope Area Ratio (Straube, 2012)

A research conducted a number of parametric analyses on a typical Saudi Arabian residential building (Al-Saadi and Budaiwi, 2007). In one analysis, researchers investigated the influence of building orientation on energy consumption of the base case building for Dhahran and Riyadh. The base case building initially being south-north oriented was later changed to east-west orientation. Found was an increase in the energy consumption of 1.8% and 2.2% in Dhahran and Riyadh for east-west orientation respectively. It was then concluded that the south-north orientation was the best for residential buildings in hot climates. The orientation in conjunction with the building's form factor can help reduce energy consumption to a greater extent.

As mentioned earlier, insulation is the most important determinant of energy savings without the compromise of thermal comfort. The surface of building envelope is exposed to the exterior environment and poses greater risk of heat gain or loss depending on its thermal properties. Thermal insulation is a material that reduces this risk thereby reducing heating and cooling loads. As walls and roof together form almost an integral part of building envelope, the potential for heat gain or loss is usually high and thus the envelope needs to be thermally insulated. As a part of passive strategy, a technical report reviewed and summarized the state of understanding of enclosures with higher values of thermal resistance (Straube and Smegal, 2009). High R-value enclosure was defined as the one that attempts to bring exceptionally good control of heat flow through walls, roof, windows and foundations. This could be achieved only when the enclosure has high R-value insulation installed within the respective assembly. The requirements that define a high R-value enclosure include *thermal continuity/thermal bridging, airtightness, durability, quality of construction, comfort* and, *economic aspects*. Thermal continuity of insulating material reduces the risk of thermal bridging by avoiding the increased rate of heat transfer. Airtightness of a building needs to be increased when thermal insulation with increasing values is used in the envelope. Likewise durability, quality of construction, comfort and economic aspects hold their positions in defining a high R-value enclosure.

A comparative analysis of exterior wall coupled with thermal mass was undertaken (Lerum, 2010). The walls were arranged such that the outer wall was a traditionally insulated one followed by thick thermal mass wall towards the interior. The analysis of this configuration of walls presented findings of coupling of exterior wall assembly with

high mass interior wall. The energy performance results show that the energy use was quite consistent with a total specific energy use of 152-198 kWh/m²yr for the years 2001-2004. The annual heating energy use was also compared to monthly heating degree days (HDD). The results show greater difference from winter to summer period than the HDD.

An all year round energy performance and thermal comfort study was carried out on the behaviour of solar walls in a residential building for Mediterranean climatic conditions (Stazi et al., 2012). The study aimed to investigate the influence of a Trombe wall's thermal behaviour and its influence on heating and cooling energy needs. Parametric approach was also included by varying thermal insulation level of the envelope. A series of activities were carried out to meet the set objectives including various operating schemes of the solar wall. **Figure 2.5** shows the arrangement of Trombe wall as thermal mass for summer and winter months.

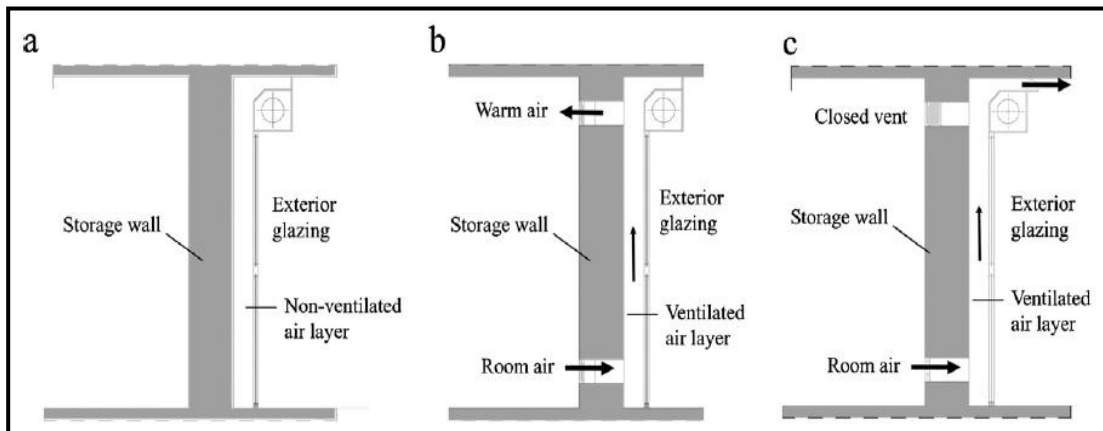


Figure 2.5: Trombe Wall Arrangement: a) Non-Ventilated; b) for Winter; c) for Summer (Stazi et al., 2012)

As a result of all necessary arrangements, the solar wall provided heating energy savings and thermal comfort in winter and intermediate seasons. The performance of solar wall

degraded in summer due to high heat storage risk within it. The wall in this case needed to be screened from direct sunlight and cross-ventilated.

Active Dynamic Air Envelope (ADAE) is a completely new idea facilitating energy performance improvements and thermal comfort enhancement of buildings in bidirectional climates (Yu et al., 2011). The ADAE is a composite envelope system consisting of a mechanically ventilated air gap within the envelope system. It is intended to take away the radiative heat that otherwise is transferred through the air gap to the inner construction materials and finally into the occupied space. Khanal and Lei, 2011, presented an overview on passive strategy for natural ventilation using solar chimney. The concept behind solar chimney is that it traps heat from the sun and enhances the buoyancy effect for passive ventilation. The review took into consideration the effects of channel geometry on ventilation and effect of chimney tilt angle on thermal performance.

Roof covered with vegetation is known as green roof and has started to become a valuable passive strategy to reduce roof heat transfer and improve thermal comfort these days. These are of three types namely modular, intensive and extensive. The modular systems are comprised of trays of vegetation that are spread all over the roof as required. The growing medium in this type of green roof system comes in various depths. But the modular systems are not as popular as the other two systems, intensive and extensive. While the extensive green roof system is a light weight construction having comparatively less variety of plant types with little maintenance and little human intervention, the intensive green roof system is a heavy weight construction depicting a garden like environment over the roof. This allows the availability of a variety of plant types. Another difference among the two is that the extensive system has growing media up to a depth of

approximately 6 inches and intensive systems use the growing medium of 8 inches or more. A typical green roof system could be seen in **Figure 2.6**. Irrespective of the type of green roof, typical layers or construction of all systems, especially extensive and intensive, include the following layers: *vegetation, growing medium, filter membrane, drainage layer, root barrier, water proof membrane, cover board, thermal insulation, vapour barrier* and *structural support*.

Presented in a research were cost savings by green roofs in arid climates (Kamel et al., 2012). Effectiveness of green roof on energy consumption of residential building was studied in Cairo. The study comprised of both theoretical and experimental analyses. Theoretical analysis was performed by conducting detailed thermal simulations for various green roof configurations using DesignBuilder. Experiments were conducted on two story residential building. Parametric analyses performed in the theoretical part of the study included the following: *thickness of green roof soil, conductivity of green roof* and *building aspect ratio*.

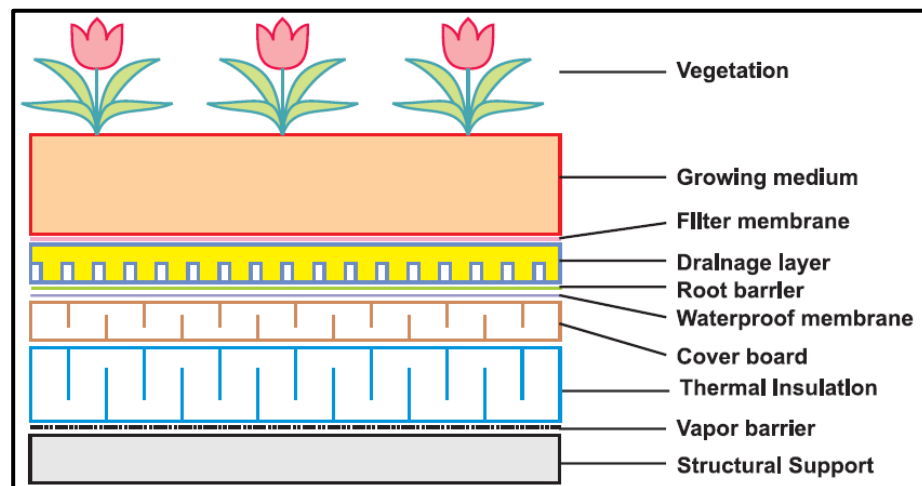


Figure 2.6: Typical Green Roof Construction (Wong and Hogen, 2011)

It was found that cost savings of the green roof ranged from 15-32% compared to traditional roof. There wasn't any major impact of the aspect ratio of the building on savings whereas variation of the thickness of the soil in green roof proved to be energy efficient. Thinner soil was better in energy conservation compared to thicker one but proved thermally uncomfortable in winter season. Heating costs as a result of thinner soil were high but net savings were far greater. The soil conductivity proved to be best in enhancing energy performance. Decrease in thermal conductivity resulted in an increase in energy performance of the roof.

A study analysed and compared thermal benefits of different green roof samples in order to evaluate the energy savings of buildings (Celik et al., 2010). Data was collected from on-going green roof projects and used in the theoretical analysis. The green roof systems were modelled with three types of growth media that were matched with three sedum types, as shown in **Table 2.1**, which finally resulted in nine combinations.

Table 2.1: Growth Media and Vegetation (Celik et al., 2010)

Growth Media	Vegetation Species
L – Lava	S – Sedum spurium
A – Arkalyte	K – Sedum kamtchaticum
H – Hadite	A – Sedum sexangulare

A complete thermal analysis model was built and heat flux calculations were performed. The study concluded significant cooling energy savings for the building's air-conditioning system based on the right combination of growth media and vegetation species. Temperature readings of a black roof membrane were also recorded as a reference. As shown in **Figure 2.7**, LS combination had best roof insulating characteristics.

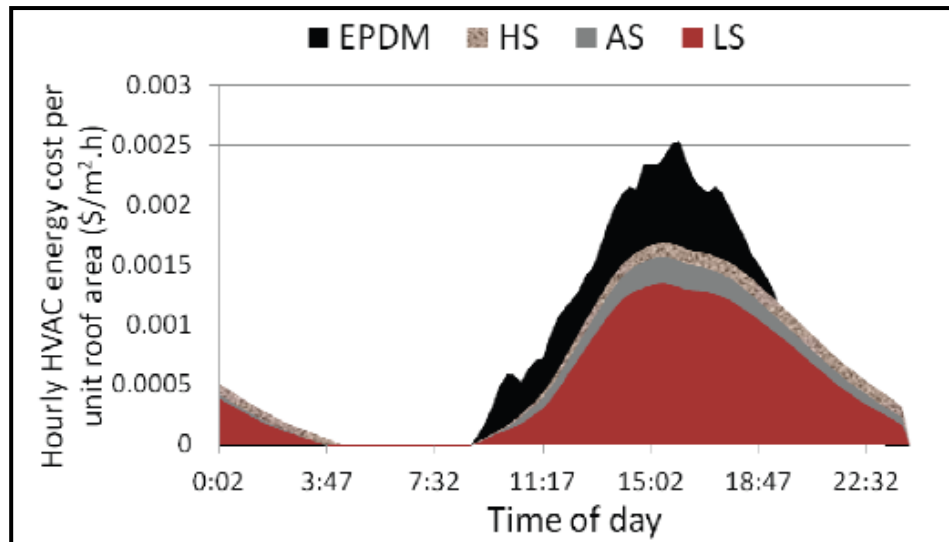


Figure 2.7: Air-Conditioning Energy Cost (Celik et al., 2010)

Another study looked into the impact of green roof on building energy performance for a single family house in a temperate French climate (Jaffal et al., 2012). The roof slab temperature amplitude and heat flux through the roof in summer, and heat losses in winter were found to be reduced upon using green roof. The indoor temperature and annual energy demand were reduced by 2% and 6% respectively. The study also showed high dependency of thermal impact on insulation used in the roof concluded its benefits and suitability for hot, temperate and cold European climates.

2.3 PV/T & BIPV Systems

A unique research endeavour was undertaken at the University of California on the effect of installing solar PV panels on roof heat transfer (Dominguez et al. 2011). The work done was somewhat similar to the work done in a study mentioned earlier in this section (Witmer and Brownson, 2011). Quantified in this research were indirect benefits of rooftop PV systems for building insulation. The roof of the building was partially covered with PV panels and measurements of thermal conditions throughout the roof profile were

conducted. As shown in **Figure 2.8**, the study also incorporated thermal imagery to demonstrate ceiling temperatures of exposed and under the PV panel roof. The daytime ceiling temperatures of the roof under PV panels were 2.5 K cooler than the exposed roof. At night time, the exposed roof was found to be cooler than the roof under the PV panels. This showed roof insulation properties as a result of PV installation. Significant heat flow reductions were observed during the daytime under the PV panel. The study did not yield any advantage for the winter season for annual heating load but resulted in a huge advantage for the summer season for annual cooling load. A benefit of 5.9 kWh/m² with a reduction of 38% in annual cooling load was estimated. The strategy of installing a PV array in this study helped reduce thermal stresses on the roof besides reducing energy consumption and improving thermal comfort.

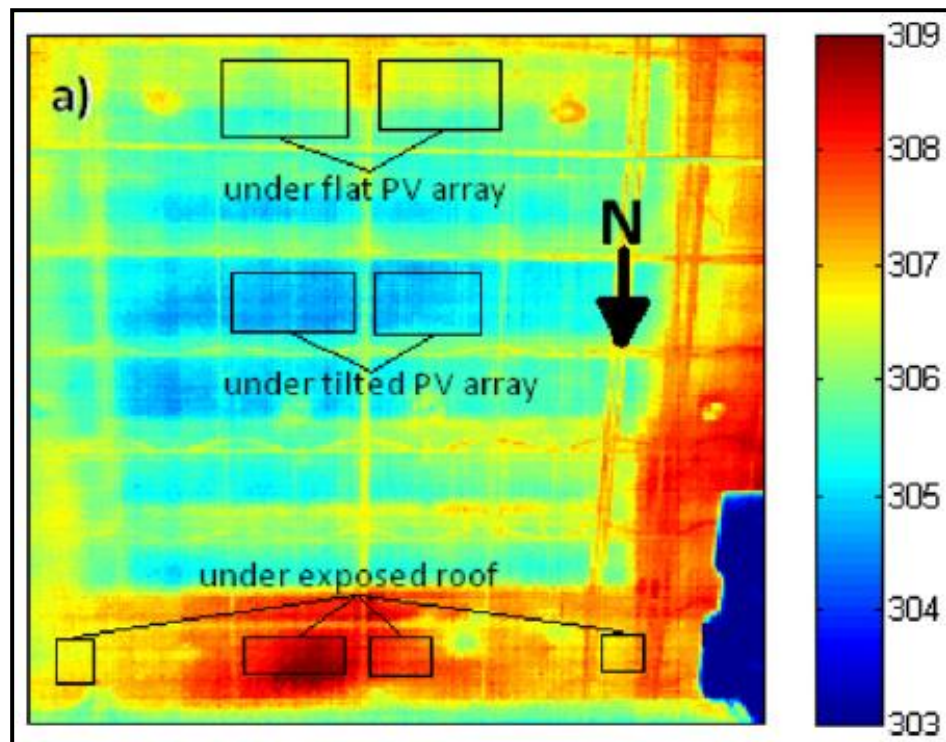


Figure 2.8: Infrared Imagery of the Roof w/ and w/o PV Panel (Dominguez et al., 2011)

Studied, examined and quantified in a research were the effect of shading of building integrated PV (BIPV) on roof surface temperature and heat transfer on a university building (Vardoulakis and Karamanis, 2012). Mean hourly temperature difference of 15°C was observed in summer between the shaded and exposed portions of the roof. PV panels installed on roof saved huge amounts of cooling energy during hot summer days besides producing electricity. The measurements were carried out for 11 days at different locations on the shaded portion of the roof. Evidence for the insulating properties of PV panels on the roof surface was concluded. Another study carried out in Milano demonstrated the integration of PV in the building thereby making the investment cost effective based on the analysis of a case study that was still under development (Adhikari et al., 2012). The applied energy performances were lower than the estimated ones. This techno-economic analysis calculated the net present value (NPV) of the building and portrayed its economical validity in a short period of time of about 15-20 years compared to a similar building. Direct and indirect benefits of installing PV systems on existing residential homes in northern climates were provided in a research study (Yimprayoon and Navvab, 2010). The solar irradiation at such places is usually found to be less and makes it hard for people to believe the feasibility of PV systems. The researchers concluded with investment paybacks of PV systems in near future. They also mentioned the importance of installing these systems into the building skin which could accelerate the investment paybacks.

With the advantageous aspects of the aforementioned studies, the PV systems should hold good for use in the current research of nZEB. Hence, one needs to know the viability of PV systems in Saudi Arabian climatic conditions. Explored were the renewable energy

options and viability of solar PV in the residential sector in Saudi Arabia (Al-Saleh and Taleb, 2009). The study adopted a timeframe of about 15 years starting from the year 2010 in order to look into the prospects of PV for Saudi Arabian homes in future. Two possible scenarios were considered: *introduction of energy efficiency means* and *continued absence of energy efficiency means*. They concluded with apparent significant economic benefits to the country and environmental benefits to the world. With regard to the scenarios considered in the discussion above, the residential buildings built in Saudi Arabia have poor thermal performance indicators. Most of the buildings are still used in continued absence of energy efficiency means and thus require the introduction of the same. Although it is very difficult, but not impossible, to improve the energy performance of an existing building, the number of residential buildings to be dealt with makes it impossible. The scenarios considered seem to be very much valid if the future of Saudi Arabia as a sustainable economy is to be considered, and the prospect of solar PV holds good for that.

On the other hand, the status and potentials of renewable energy applications in Saudi Arabia were addressed by considering wind and PV (Said et al., 2004). Their efforts pointed out that there was no reasonable progress in solar PV utilization due to many reasons besides the experience gained in this regard by initiating solar energy projects at various locations in the Kingdom with the help and support of Energy Research Institute (ERI) at King Abdel-Aziz City for Science and Technology (KACST). Cited in the work of Said et al. were the obstacles to solar energy utilization. These included the following: *wide availability and superiority of oil over solar energy as a source of energy and its relatively low cost, dust effect, lack of awareness of renewable energy among the public,*

etc. Among the concluding remarks was the idea of low and medium solar thermal application which already has been found technically and economically feasible in Saudi Arabia.

A similar kind of effort was undertaken to explore renewable energy potentials in Saudi Arabia with an aim to promote Zero Energy Residential Buildings (ZERB) (Alrashed and Asif, 2012). In order to accomplish their task, the authors provided detailed account of energy profile of Saudi Arabia, discussed the fundamental features of ZEB and reflected the obstacles in the development of ZEB. Lastly recommendations were given to pave way for renewable energy. Some of these include *awareness, education, feasibility studies*, etc. A study addressed the importance of integrating the building, existing or new, with solar energy systems was shown in a more recent research (Lopez and Frontini, 2013). Lessons were presented from various research projects by Institute of Applied Sustainability to the Built Environment (ISAAC) to promote energy efficiency by utilizing PV, solar thermal and solar passive systems on historical buildings. The main goal behind this was the renewable energy supply. Aspects to be considered while integrating the solar energy systems in historic buildings were highlighted. These include *co-planarity with the building surface, respect of the lines, compliance with the proportions to avoid random solar installation, grouping for better integration, accuracy of connecting elements, visibility from other buildings and streets*.

The renewable energy options, potentials and aspects of integration as discussed above could be taken further by considering PV technology for implementation in Zero Energy Homes to meet reduced energy demands and approach to zero energy.

2.4 Building Performance Simulation (BPS) Tools for ZEB Design

Building performance simulation could be described as an increasingly used tactic to analyse energy performance of buildings without compromising thermal comfort (Maile et al., 2007). A study was carried out to develop net-zero energy code for Tucson using computer simulation programs (Chalfoun et al., 2011). The aim was to reduce the energy consumption of the state through perspective and performance compliance paths and to emphasize on how energy simulation can influence and inform the design process of buildings. As discussed in the design strategies section of the report, four major steps were set that resulted in pre net-zero energy status for various building prototypes that were of interest to the study finally resulting in net-zero compliance. The first step in developing the guidelines was the determination of appropriate energy modelling software tool that had capabilities suitable for the design of net-zero energy buildings. The software that demonstrated capabilities to simulate passive solar design was considered as the first step in net-zero energy design. With the help of the software selected, a total of more than 75% energy savings were observed without the use of PV technology. Keeping this in mind one can understand the importance of using software tool to assess the energy performance of a building design to achieve pre net-zero status. The pre net-zero status in conjunction with appropriate renewable technologies would then achieve net-zero compliance.

As advancements in software tools have aided in design decision making, one must never forget to consider the effect of modelling approach on building's loads assessment and capabilities of the software tool. This otherwise will undoubtedly affect the decision making during the design phase. Conversion of real building geometry into an energy

model often results in neglecting and underestimating the translation effects (Dipasquale et al., 2013). The building's geometry definition on the assessment of loads was investigated. Discussed were the effects of number of floors, internal walls and thermal capacitance, façade sizes and thermal bridging, and zone numbers during simulation. Worth noting was the reasoning behind the effect of number of zones on building loads. Large impact on building loads was observed upon reducing the whole floor to only one thermal zone for simulation. The building geometric model with only one thermal zone of course simplified the case but affected the assessment of heating and cooling demands by 12.5% and almost 22% respectively.

On the other hand, one of the main considerations to be given to the selection of a software tool is the analytical models or mathematical formulations on which its simulation engine is based. These define the capabilities of the software tool in question. Though there were many simulation engines earlier, it was DOE 2.1E that grabbed the attention and was widely used for a period of 30 years. Later U.S. Department of Energy started developing EnergyPlus that combined best features and capabilities of DOE 2.1E and BLAST (Crawley et al., 2004). Described in a paper was the selection of energy simulation engine and a discussion on its usage over different life-cycle stages (Maile et al., 2007). The purpose of simulation engine is to support building design by comparing energy consumption of different design alternatives. Both DOE 2.1E and EnergyPlus provide such capabilities but differ from each other on various grounds. **Table 2.2** illustrates few functionality differences between them.

Table 2.2: Functionality Differences between DOE 2.1E and EnergyPlus (Maile et al., 2007)

S. No.	Functionality	DOE 2.1E	EnergyPlus
1	Space load calculation method	Weight factor method	Heat balanced based approach
2	Loads & systems connectivity	No	Integrated loads & systems simulation
3	HVAC systems definitions	Predefined	Flexible; Component based
4	HVAC controls	Simplified representation	More flexible controls
5	New HVAC technologies	No detailed natural ventilation; No under floor air distribution system	Moisture absorption & desorption; solar components; natural ventilation
6	Interconnectivity to other tools	None	Links to COMIS & SPARK
7	Time step	1 hour	Dynamic (ranges from 1 min to 1 hour)
8	Interoperability	No	Yes

Loads and systems connectivity functionality is very important as its availability in a simulation engine explains the inter-connectivity and integration of loads and systems at the time of simulation. This helps model real life scenarios which eventually lead to real time results. Similarly, the other functionalities mentioned in **Table 2.2** have their own advantages and disadvantages depending upon their level of availability in the simulation engine. It could be observed that the simulation engine “EnergyPlus” is the developed trend in energy simulations and must be used in building design.

A research contrasted the capabilities of building energy performance simulation programs (Crawley et al., 2008). An up-to-date comparison of the features and capabilities of the most used building energy programs was provided and was based on the following categories: *general modelling features, zone loads, building envelope,*

HVAC systems, electrical systems & equipment, economic evaluation, environmental emissions, etc. The building energy simulation programs that were considered included *BLAST, BSim, DeST, DOE 2.1E, ECOTECT, Ener-Win, Energy Express, Energy-10, EnergyPlus, eQuest, ESP-r, IDA ICE, IES <VE>, HAP, HEED, PowerDomus, SUNREL, Tas, TRACE* and *TRNSYS*. Weytjens and colleagues compared six BPS tools based on the architect-friendliness (Weytjens et al., 2010). The study was carried out concerning net zero energy buildings to provide early design support for architects. The tools that were examined included *ECOTECT, IES/VE – Sketch-Up, Energy10, eQuest, HEED* and *DesignBuilder*. Certain criteria were set to define the user-friendliness of the tools. The results showed that no tool was entirely adequate for architect's use. Worth noting here was the selection of DesignBuilder among the six tools for comparison. DesignBuilder provides a graphical user interface (GUI) to today's widely used energy simulation engine EnergyPlus.

Another study compared different BPS tools for architect-friendliness based on online survey (Attia et al., 2009). The survey took into consideration ten tools and received 249 valid responses. Among the tools considered were *ECOTECT, HEED, Energy 10, Design Builder, eQUEST, DOE-2, Green Building Studio, IES VE, Energy Plus* and *Energy Plus-SketchUp Plugin (OpenStudio)*. Two issues were set forth: *Usability and Information Management (UIM)* and *Integration of Intelligent Design Knowledge-Base (IIKB)* of the software tools. It was found that architects preferred IIKB over UIM in the tool's interface. Highest numbers of responses were from architects and designers and many were from LEED accredited professionals. Questions like *one's position, tools they use, etc* were asked in the survey. It was noted that DesignBuilder was used by approximately

22% of the respondents. It was also considered as a tool that was used in early design phase by the respondents. The tools were grouped into three categories and results revealed that DesignBuilder was ranked in the second category with a slightly less agreement among the respondents for architect-friendliness even though it was popularly known to have friendly GUI and varied graphical output features.

A summary of the selection criteria of BPS tools based on architects' and engineers' perspective of the requirements of the tool was presented in a research publication (Attia et al., 2012). It might be possible that an architect's requirements of a tool could be least important to engineer's requirements. Results indicated a wide gap in between architects' and engineers' requirements of the tool. It was found that the architects look for architectural design issues such as *exterior shading, passive heating/cooling, natural ventilation, building shape and massing, etc* in a tool. But engineers put in entirely a different perspective. They look for *HVAC systems, controls, glazing options, insulation, etc*. The comparison of "six" and "ten" BPS tools respectively in the aforementioned paragraphs discussed the architect-friendliness but not engineer-friendliness. This means that DesignBuilder which was slightly under-rated may be highly-rated by engineers depending on its functionalities.

Use of BPS tool in the design of NZEBs has become absolutely necessary during the early design phase (Attia and De Herde, 2011). Ten early design tools were compared with the aim of using and integrating them during the design of NZEBs. The inclusions were *HEED, e-Quest, ENERGY-10, Vasari, Solar Shoebox, Open Studio Plug-in, IES-VEWare, DesignBuilder, ECOTECH* and *BEopt*. Two criteria sets were considered; the first being a collection of five criteria namely usability, intelligence, interoperability, accuracy

and design process integration, whereas the second being the design matrix for NZEB. Also discussed was the NZEB tools matrix, as shown in **Table 2.3**, which incorporated most recurring early design features addressing the aspects such as *metrics, comfort level & climate, passive strategies, energy efficiency, renewable energy systems and innovative solutions & technologies*.

Table 2.3: NZEB Tools Matrix (Attia and De Herde, 2011)

NZEB Criteria	HEED	eQUEST	Energy 10	Vasari	Solar Shoebox	Openstudio	IES VE-Ware	ECOTECH	DesignBuilder	BeOpt
Metrics	•	•	•	•	•	•	•	•	•	•
Energy	•	•	•	•	•	•	•	•	•	•
Environmental (CO ₂)	•	•	•				•		•	•
Economic	•	•	•						•	•
Embodied Energy										
Urban Scale NZEBs										
Comfort & Climate	•	•	•		•		•	•	•	•
Climate Analysis	•	•	•	•			•	•	•	
Static	•	•	•	•			•	•	•	•
Adaptive					•					
Comfort Visualisation					•			•	•	
Passive Solar	•	•	•	•	•	•	•	•	•	•
Geometry & Massing				•	•	•	•			•
Daylighting	•	•	•				•		•	
Natural Ventilation	•		•				•		•	•
WWR		•	•				•		•	•
Thermal Mass	•		•				•		•	•
Shading Devices	•	•	•			•	•	•	•	•
Energy Efficiency	•	•	•	•	•	•	•	•	•	•
Envelope Insulation	•	•	•	•	•	•	•	•	•	•
Glazing Performance	•	•	•	•	•		•	•	•	•
Envelope Air Tightness	•	•	•				•	•	•	•
Artificial Lighting	•	•	•				•		•	•
Plug Loads	•	•	•				•		•	•
Infiltration Rate	•	•	•		•				•	•
Mechanical Ventilation	•		•						•	•
Cooling System	•	•	•	•			•		•	•
Heating System	•	•	•	•			•		•	•
Renewable Technologies	•		•		•		•			•
PV (PV)	•		•		•		•			•
BIPV										

Solar Thermal			•				•			•
Innovative Solutions & Technologies					•		•			•
Mixed Mode Ventilation					•					
Advanced Fenestration							•		•	
Green Roofs							•		•	
Cool Roofs	•									
Double Skin Facades									•	
Solar Tubes										
Phase Change Materials									•	

As can be seen from **Table 2.3**, DesignBuilder and IES VE-Ware are the tools that provide most of the design features addressing the aforementioned aspects. With the increasing use of EnergyPlus simulation engine, DesignBuilder being able to provide a GUI to this engine, and strong design features that address NZEB design aspects; DesignBuilder holds good for carrying out performance based analyses to design NZEB as the first step. The next step, however, would be to use another tool that addresses PV and BIPV technologies. It was noted from the literature in the previous paragraphs that DesignBuilder was considered by the respondents as a tool for early design phase. Seen from Attia and De Herde in the literature above was the use of BPS tools in the design of NZEBs during the early design phase. This directly compliments the abilities of DesignBuilder for the work to be carried out. The forthcoming paragraphs discuss various BPS tools that were of interest to the research being carried out.

2.4.1 DesignBuilder

DesignBuilder as mentioned earlier is a tool used in early design phase. It provides a GUI to today's widely used energy simulation engine EnergyPlus and is popularly known to have varied graphical output features. It has strong design features that address the design aspects of NZEBs that hold it good for carrying out parametric and performance based analyses. The strengths, weaknesses and data exchange capabilities of DesignBuilder

illustrated that the simulation program had most comprehensive user-interface for the most widely used energy simulation engine EnergyPlus (Maile et al., 2007). The illustration was based on four grounds namely *tool architecture & functionality*, *life-cycle usage*, *data exchange & interoperability* and *limitations*. Portrayed in a graphic was the information workflow in DesignBuilder. The workflow starts with selecting a location for carrying out the analysis. Then the tool allows the creation of building geometry and other definable parameters such as *internal loads*, *construction types*, *windows*, *doors*, *lighting*, *material selection*, *HVAC systems*, etc. This can be seen in **Figure 2.9**.

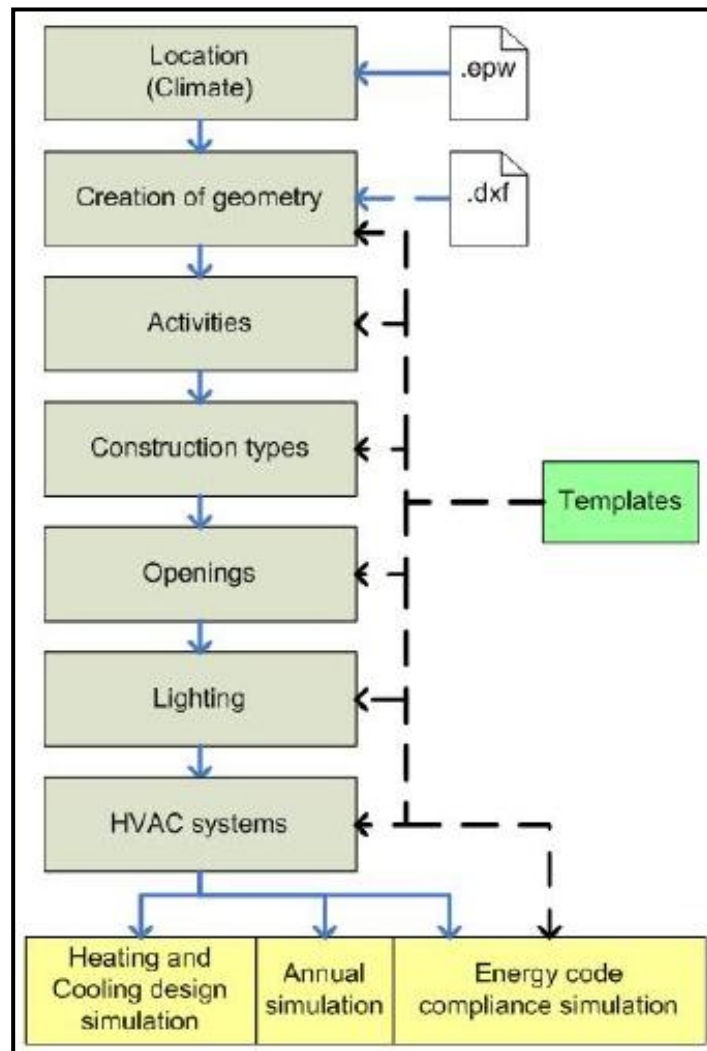


Figure 2.9: Information Workflow in DesignBuilder (Maile et al., 2007)

DesignBuilder even supports DXF file format to model the building using its footprint. It is appropriate for beginners as it provides help contents within its user-interface. DesignBuilder could be used in all phases of the design. It also provides modelling of more complex geometries that is difficult to achieve with other BPS tools. The major limitation that hinders the capability of DesignBuilder is the inability of the tool to import EnergyPlus input files. This therefore leads to the development of a geometric model separately.

With DesignBuilder set for conducting first phase of research activities, it is now time to search for a tool that addresses PV technology. Among the many state-of-the-art tools related to renewable technologies, two tools grabbed the attention. One is TRNSYS that is capable of integrating the PV systems into the building geometry whereas the other is HOMER that is capable of sizing PV system depending on the load requirements. The key in selecting appropriate tool for the second part of research is the perfect match and fit of these tools with the functionalities of DesignBuilder. Each is discussed separately in the subsequent paragraphs.

2.4.2 TRNSYS

TRNSYS is a widely used tool that provides a complete and extensible simulation environment for transient simulation of systems and multi-zone buildings to validate new energy concepts. It has been used for the past 35 years and is being used with an ever increasing interest among researchers. It is used for the following applications: *solar systems (PV/T), low-e buildings, HVAC systems with advanced design features, renewable energy systems, etc.* TRNBuild is the program among the various suites of TRNSYS that is related to the building's user interface and description. It helps in specifying the details

of the structure of the building such as *windows & its properties, heating schedules, cooling schedules, etc* and simulates the thermal behaviour of the building. Though TRNSYS covers a number of building related concepts, its simulation engine is not based on EnergyPlus. It is not included in the NZEB tools matrix either. Crawley and Hand contrasted the capabilities of 20 building energy performance simulation programs (Crawley et al., 2008). The comparison of the tools was based on a variety of categories. EnergyPlus and TRNSYS were present in the comparison study. The results indicated that the features or capabilities of EnergyPlus that were in common use were more when compared to TRNSYS. It was also noted that TRNSYS had few features or capabilities whose input requirements were difficult to obtain. There were also few features or capabilities of TRNSYS that required domain expertise unlike EnergyPlus. Many features in the daylighting and controls were absent in TRNSYS unlike EnergyPlus. TRNSYS also lacked functionality in a number of features in the zonal air distribution units.

2.4.3 HOMER

HOMER is a hybrid micro-power optimization model for electric renewable that analyses available electric renewable technologies either individually or in combinations (Givler and Lilienthal, 2005). It is an optimization model that carries out a number of sensitivity analyses and identifies cost-effective solutions to energy requirements. The following are required for HOMER as inputs: *cost and performance characteristics of the desired components, daily and monthly load profile and renewable resource*. The selection of the desired components for analysis is the foremost step prior to inputting the details in HOMER. It has the flexibility of selecting individual or multiple component systems besides allowing one to input the information at varying levels of details. Another

important feature present in HOMER is its evaluation of potential design options for both off-grid and grid connected power systems for remote, stand-alone and distributed generation applications. As the thesis research on nZEB incorporates PV technologies, HOMER can help size PV system depending on the daily load profile of the building which eventually could be helpful in determining the area requirements for PV systems installation.

In conclusion, one needs to use a tool that is capable of simulating a wide variety of passive solar techniques to design a ZEB. DesignBuilder provides such capabilities in a broader and detailed manner with the help of its energy simulation engine EnergyPlus. The next step would be to take advantage of PV technology. This could be achieved either by using TRNSYS or HOMER. Two options can be considered. Scenario #1 considers the use of DesignBuilder for passive techniques utilizing typical design strategies and TRNSYS for integrating renewable PV technologies into the building structure. Scenario #2 considers the use of DesignBuilder for passive techniques and HOMER for sizing the renewable PV technology. Each option is discussed in the subsequent paragraphs.

Option #1: DesignBuilder & TRNSYS

With regard to the first scenario, both the tools do not make a perfect match and fit. If TRNSYS was to be used for PV technology integration then why would one use DesignBuilder for building performance simulations separately? TRNSYS in that case could perform all the required building performance simulations by integrating PV systems. As DesignBuilder was selected for first phase of research activities and seemed advantageous, one must not use TRNSYS for second phase of research activities. This is because building simulation results of both the tools differ based on mathematical

formulations of their simulation engines and eventually lead to complexities while integrating PV systems.

Option #2: DesignBuilder & HOMER

With regard to the second scenario, both the tools make a perfect match and fit. DesignBuilder can perform building's energy analysis but not the feasibility of PV technology whereas HOMER can perform sensitivity analysis of PV technology depending on the load output of DesignBuilder. This output could be fed to HOMER as one of the inputs for successfully sizing PV systems to approach near-zero energy status. Various kinds of approaches may also be considered such as off-grid and grid connected systems. HOMER also helps in conducting a sensitivity analysis of real life cases, such as *effect of heat and dust on efficiency of the PV system*, which was not covered in the research due to software limitations and non-availability of appropriate tools for PV technology integration.

CHAPTER 3

BASE MODEL FORMULATION & VERIFICATION

This chapter presents the description of the house and focuses on the formulation of the base case simulation model. The house used in the study is an existing faculty residence at King Fahd University of Petroleum & Minerals; an energy efficient housing depicting the most common building design trends in the region. The chapter includes all information relevant to the development of the base case model as per the data supplied by the project contractor. It covers a wide range of data pertaining to building envelope systems, HVAC system, lighting system, equipment used in the housing, energy consumption data recording arrangements, assumptions if any, etc.

3.1 The University Faculty Housing

The building is a single family 4-bedroom faculty housing designed in the year 2008. It has two floors with a total area of approximately 377 m². The area of the ground and first floors is around 210 m² and 167 m² respectively. The floor plans of the housing can be viewed in **Figure 3.1**. The house is rectangular in shape having an aspect ratio of approximately 1:1.5 with its length at an angle of approximately 25° from the east-west axis. The orientation indication represents north. Both the floors of the house are divided into various zones depending on the functionality and needs of the occupants. The ground floor is the living area comprising of reception, dining room, study room, kitchen and laundry whereas the first floor is the sleeping area comprising of the bedrooms only. Looking at **Figure 3.1** one can notice the difference between the floor areas. The first

floor occupies less area in comparison to the ground floor and the remaining area is open to outdoors thereby allowing the possibility to accommodate the direct expansion packaged air-conditioning units.

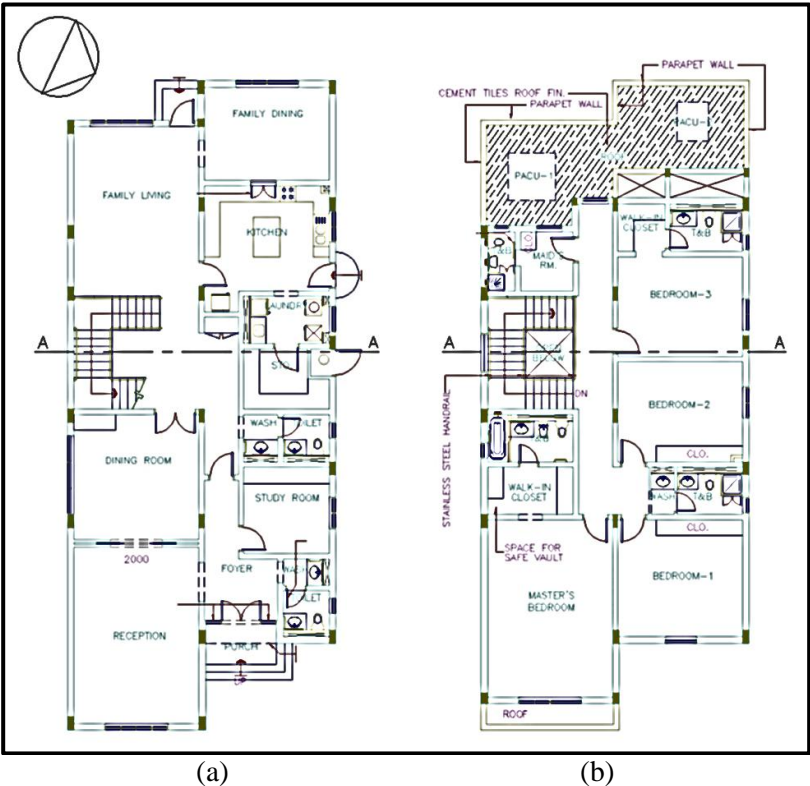


Figure 3.1: Building Floor Plans; (a) Ground Floor, (b) First Floor (Projects Department, KFUPM)

A cross-section of the house at sections A-A for both ground and first floors could be seen in **Figure 3.2** and a detailed description of the house can be seen in **Table 3.1**.

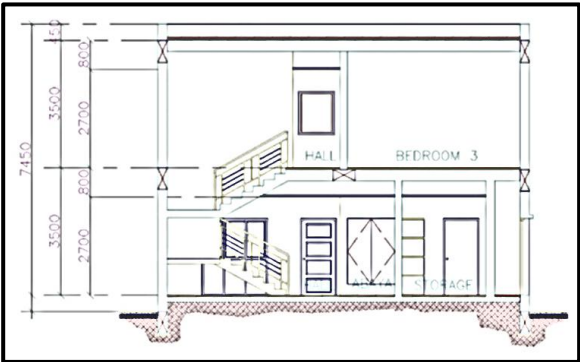


Figure 3.2: Cross-Sectional Front View of the House

Table 3.1: Building Characteristics and Specifications

Characteristics / Specification	Description of the Housing
Location	Dhahran (26.27 N latitude, 50.15 E longitude, and 17m above sea level)
Orientation	Front Elevation facing East
Shape	Rectangular
Floor to Floor Height	3.5 m
Floor Area	377.3 m ² (Gross); 210.0 m ² (Ground Floor); 167.3 m ² (First Floor)
WWR	10%
Exterior Walls	16 mm Plaster (Dense) + 100 mm Concrete Block (Medium) + 50 mm Extruded Polystyrene + 100 mm Concrete Block (Medium) + 13 mm Plaster (Lightweight)
Roof	40 mm Concrete Tiles (Roofing) + 0.2 mm Polyethylene (High Density) + 50 mm Extruded Polystyrene + 4 mm Bitumen Felt + 59 mm Cement Screed + 300 mm Reinforced Concrete (Cast, Dense)
Infiltration	1.25 ACH (Ground Floor); 0.75 ACH (First Floor)
Occupancy	7 People
Lighting Power Density	21 W/m ² (Ground Floor); 13 W/m ² (First Floor)
HVAC System Type	Residential System (Constant-Volume DX AC)

3.1.1 Building Envelope Information

This section describes the specification of the building's envelope systems as provided by the contractor. This includes the information pertaining to walls, roof, windows and floor.

3.1.1.1 Wall System

The walls of the house have the following specifications: plaster (dense) as the outermost layer, concrete block (medium) on both side with thermal insulation sandwiched in between, and plaster (lightweight) as the innermost layer. The total thickness is 279 mm with an overall U-value of 0.466 W/m²-K. The concrete blocks have been observed to be equal in thickness, however, the thickness of the plaster is varying depending on its placement in the wall assembly.

3.1.1.2 Roof System

The roof of the house has the following specifications: roofing concrete tiles as the outermost layer, high density polyethylene, thermal insulation, bitumen felt/sheet, cement screed, and reinforced concrete (dense) as the innermost layer. The total thickness is 403.2 mm with an overall U-value of $0.539 \text{ W/m}^2\text{-K}$.

3.1.1.3 Window System

The windows of the house are of the sliding panel / fixed glass plate type in an aluminium frame without thermal break. They are double glazed with two glass layers sandwiching the air layer. Glasses are light tinted and the thickness of the two glass layers is different. The total thickness is 22 mm with an overall U-value of $2.709 \text{ W/m}^2\text{-K}$.

3.1.1.4 Floor

The flooring system of the house is a slab on grade. It has the following specifications: glazed ceramic tiles as the outermost layer, cement mortar, dense reinforced concrete, high density polyethylene, and sand as the innermost layer. The overall U-value is calculated to be $0.792 \text{ W/m}^2\text{-K}$.

3.1.2 Cooling System Information

This section describes the characteristics and specifications of the building's cooling systems. This includes the information pertaining to the capacity (tonnage), supply air and outside air requirements, and temperature set-points of constant-volume direct expansion air-conditioning units. Each floor is served by the one unit thus requiring two units for the whole house. The cooling system for the ground floor is higher in capacity, supply air, and outdoor air requirements whereas the cooling system for the first floor is comparatively lower in every aspect. Depending on the type of climate observed at the

location of the housing, the humidity control is considered as dehumidification where the hot-humid air is first cooled to get rid of moisture and then slightly heated for supply. The systems are not equipped with heat recovery or any energy efficiency measures. The air definition into each zone is based on the outside and supply air requirement as specified and shown in **Table 3.2**.

Table 3.2: Cooling System Characteristics (Projects Department, KFUPM)

Component / characteristic	Location	Capacity/Magnitude
Packaged air conditioning (Direct Expansion System)	Ground Floor	142.8 MBtu/hr = 11.9 tons
	First Floor	112.8 MBtu/hr = 9.4 tons
Ventilation	Ground Floor	Supply Air Flow: 4840 CFM = 11.3 ACH (<i>Approx.</i>) Outside Air Flow: 780 CFM = 1.8 ACH (<i>Approx.</i>)
	First Floor	Supply Air Flow: 3760 CFM = 9.4 ACH (<i>Approx.</i>) Outside Air Flow: 245 CFM = 0.6 ACH (<i>Approx.</i>)

3.1.3 Lighting System Information

This section describes the specifications of the building's lighting systems and includes the information pertaining to the types of lighting fixtures, total wattage, and lighting power density in each zone. The ceiling and wall luminaires and lighting outlets range from recessed light bulbs, mirror light, surface mounted fluorescent lamps, exterior wall lights to chandeliers. The wattage of each depends on the type of fixture and purpose. Summing up the wattage of all the light fixtures, a total of 4278 Watts has been calculated specifically for the ground floor. The wattage for the first floor is calculated to be 2168 Watts. **Table 3.3** shows the lighting power density based on the specification of each lighting fixture in each zone.

Table 3.3: Lighting System Characteristics

Level	Lighting Load (W)	Lighting Power Density (W/m ²)
Ground Floor	4278	Wattage / Floor Area = 4278 / 205.7 = 21
First Floor	2168	Wattage / Floor Area = 2168 / 171.6 = 13

3.1.4 Equipment Information Summary

This section describes the specifications of the equipment used in the house in terms of power requirements. **Table 3.4** shows the summary of equipment specifications.

Table 3.4: Equipment Specification (Projects Department, KFUPM)

Equipment	Equipment Load* (kW)
Refrigerator	1.00
Deep Freezer	1.20
Electric Stove (Cooking Range)	6.00
Electric Stove Hood (Range Hood)	1.00
Microwave	1.00
Washing Machine	1.20
Clothes Dryer	5.00
Vacuum Cleaner	1.10
Hair Blow Dryer	0.90
TV	0.13
Coffee Machine	0.90
Tee Water Boiler	1.10

* Not all equipment load data provided by the Projects Department

3.2 Base Model Development and Formulation

This section describes the development of the base case simulation model using state-of-the-art software tool DesignBuilder with the aid of the information presented in the previous section. DesignBuilder provides a variety of tools to add and draw blocks that eventually take the shape and form of a building. However, a DXF of the original floor plans of the house was generated and imported in DesignBuilder to start with. All it

needed was to trace the imported dxf to generate each level of the house separately. This step by step approach, initially, eased the process of building the house model. Though there were a number of zones in the house, each floor was considered as one single zone for simplicity. **Figure 3.3** shows the developed model of the house with the orientation indicator representing north.

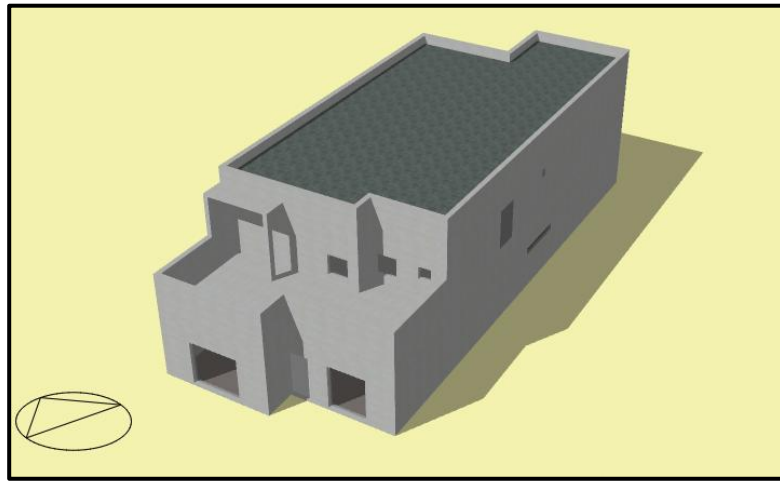


Figure 3.3: 3-D Rendering of 4-Bedroom KFUPM Faculty Housing

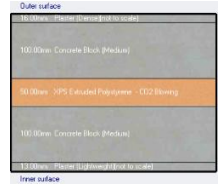

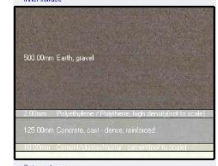
The forthcoming paragraphs explain every aspect of the base model development from the view point of building envelope systems, HVAC system, lighting system, and equipment definition.

3.2.1 Building Envelope Construction

Based on the specifications mentioned in the previous section, the construction of building envelope systems in DesignBuilder is described and discussed here. This includes the details of each surface composition, i.e. wall, roof, window and floor. **Table 3.5** shows the summary of construction features of each thermo-physical system. In addition to these, emphasis is also given to infiltration in terms of airtightness depending on the number of openings, and organization and usage of the house. The airtightness in

DesignBuilder is expressed in terms of a constant rate ac/h schedule. Each floor has been assumed to have different levels of airtightness. Though the standard value these days for airtightness has been adopted as 0.5 ACH, the same could not be observed in case of the base model development.

Table 3.5: Summary of Construction Features of Wall, Roof, Window and Ground Floor

Envelope System Type	Layers (Outside to Inside)	Thickness (m)	U-value (W/m ² -K)	Image
Wall	Plaster, dense	0.016	0.466	
	Concrete Block, medium	0.10		
	Extruded Polystyrene	0.05		
	Concrete Block, medium	0.10		
	Plaster, lightweight	0.013		
Roof	Concrete Tiles, roofing	0.04	0.539	
	Polyethylene, high density	0.0002		
	Extruded Polystyrene	0.05		
	Bitumen, felt/sheet	0.004		
	Cement Screed	0.059		
	Reinforced Concrete, cast-dense	0.30		
Window	Glass, generic tinted	0.004	2.709	-
	Air Gap	0.012		
	Glass, generic tinted	0.006		
Floor	Ceramic Tiles, glazed	0.01	0.792	
	Cement Mortar	0.01		
	Reinforced Concrete, cast-dense	0.125		
	Polyethylene, high density	0.002		
	Earth, gravel	0.5		

As the lower level has many openings in comparison to the upper one, the airtightness is assumed to be 1 ACH and 0.5 ACH respectively. Besides, it is also worth discussing the modelling of sub-surface construction features of DesignBuilder. Sub-surface is an anomaly to the actual construction of the surface and provides the feasibility of modelling thermal bridging through walls, partitions and pitched roof. The application of sub-surface to the development of the base model takes into consideration the heat transfer / thermal

bridging into the space through the structure of the house. The wall specification at the points of location of columns and beams exposed to the outside environment is different in comparison to the actual wall specification. This depicts real life conditions to the heat gains into the space and correspondingly impacts cooling energy consumption. **Figure 3.4** shows the placement of sub-surfaces at the schedule of beams and footing columns on the envelope of the house.

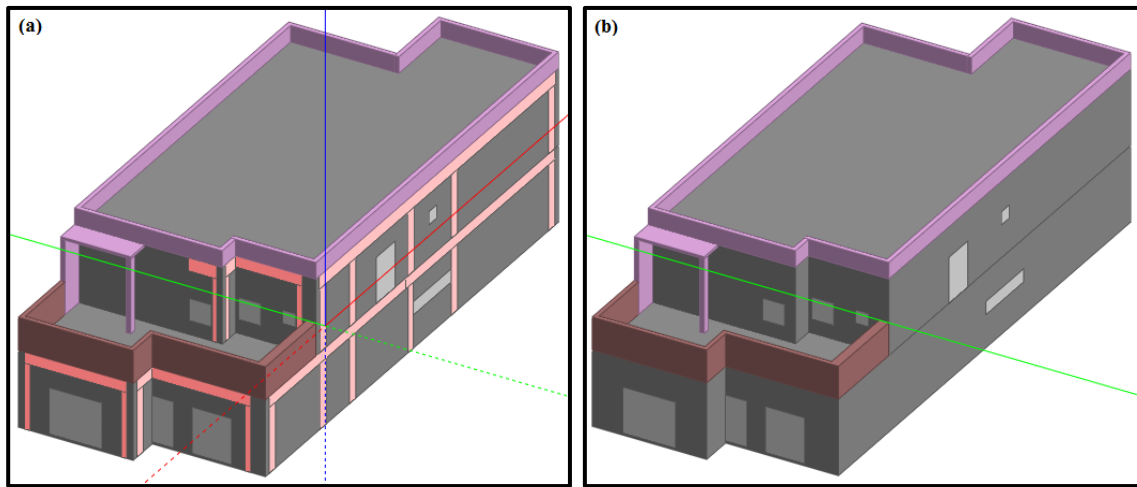


Figure 3.4: Sub-Surface Construction along the House Envelope; (a) w/ Sub-Surface, (b) w/o Sub-Surface

The building envelope comprises of walls, roof, floor, doors and windows working in tandem to deliver design performance. The definition of each envelope system in the simulation model is therefore critical. Hence, door specification of the house has also been updated into the model. Windows on the other hand have great potential for heat exchange between indoor and outdoor environment. Though the WWR of the house is calculated to be 0.1, the definition of non-specified window information makes great difference eventually and cannot be neglected. Therefore, information such as interior shading, local exterior shading devices comprising of overhangs and fins, and framing without thermal break along with glazing specification have all been modelled. However,

dividers and projection of frames was not a requirement. The glass used is double glazed light tinted with an air gap in between.

3.2.2 Cooling System Definition

DesignBuilder provides great depth for HVAC system definition with three different model data options depending on the complexity of the system. These include simple, compact and detailed. For the current base case and based on the given system information compact HVAC model definition was selected. This option allows EnergyPlus to parametrically define and model the cooling and heating systems. Critical system information such as design capacity (kW) and design flow rate (m^3/s) are sized by EnergyPlus just by providing the model with outdoor air requirements. With reference to the cooling system information presented in **Table 3.2**, outside airflow for the ground floor was considered 780 CFM. However, the outside air flow for the first floor is 245 CFM which is approximately 6% of the outside air requirement unlike ground floor. Thus, the outside air requirement for the first floor was assumed to be 414 CFM with a percentile share of approximately 11%.

The HVAC systems tab in DesignBuilder has many parameters to input. The outside mechanical ventilation airflow rate operation has five different options by either specifying it directly as ac/h or minimum fresh air requirements per person, or per area, or both inclusive. For the current scenario, ac/h was specified and outside air definition method was set depending on the zone requirements to depict real life situations. As mentioned earlier, humidity control was set to dehumidification with a control type of cool then reheat. Other information such as cooling fuel, COP of the unit, availability of the system and operation schedule were fed. The house comprised of ground and first

floors representing living and sleeping areas. Thus, separate occupancy schedules were defined for system availability and operation schedule. **Figure 3.5** and **Figure 3.6** show all occupancy schedule for ground and first floors during weekdays and weekend.

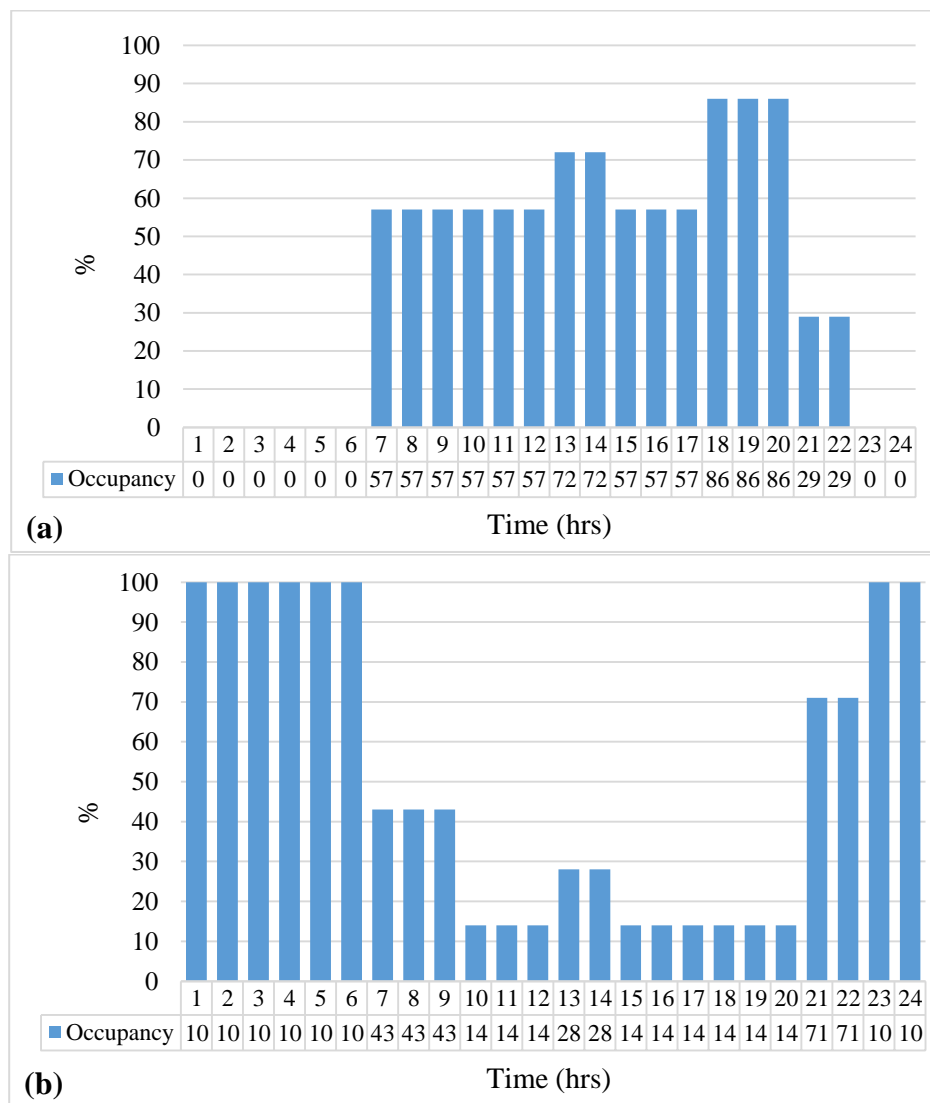


Figure 3.5: Occupancy Profile during Weekdays; (a) Ground Floor, (b) First Floor

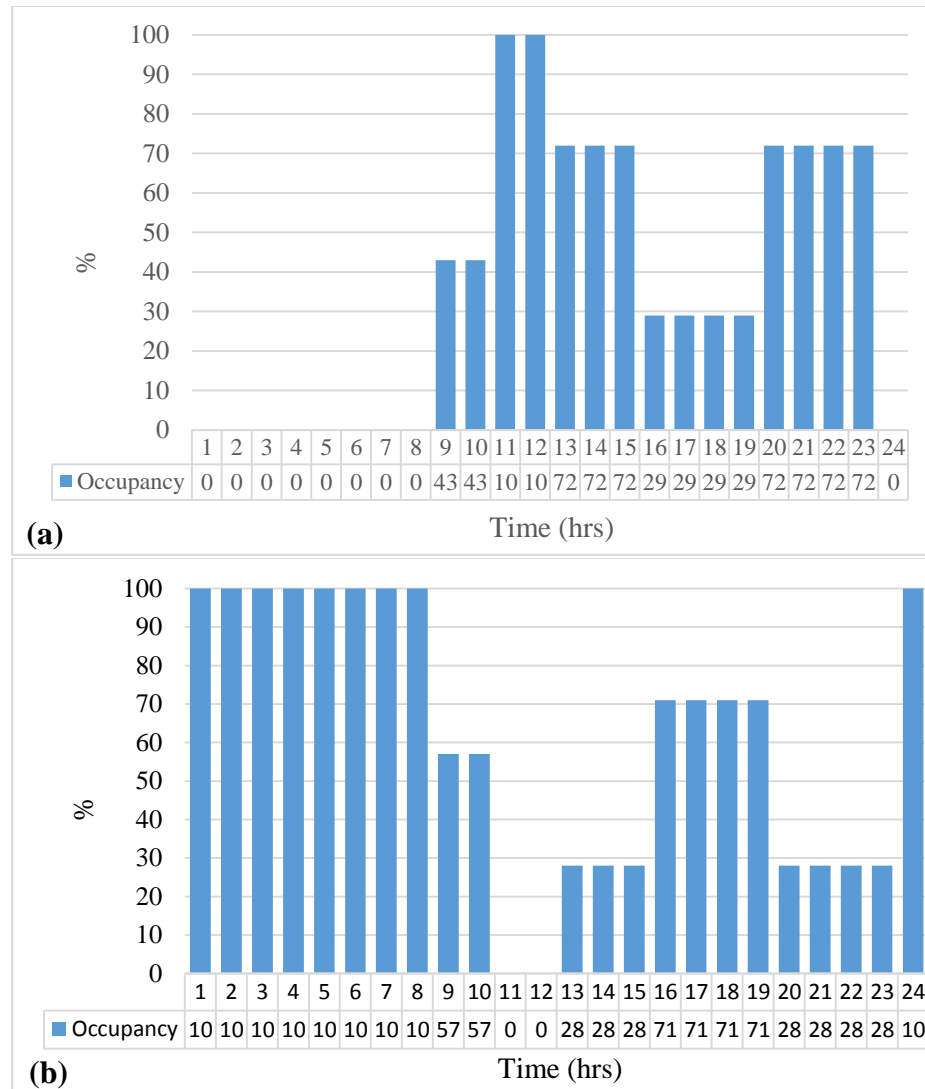


Figure 3.6: Occupancy Profile during Weekend; (a) Ground Floor, (b) First Floor

The total number of people residing in the house are assumed to be seven. The density of people is calculated to be around 0.02 people/m^2 for each level. Relative humidity control is set to 35% and 75% for humidification and dehumidification respectively. With the definition of cooling system details, and occupancy and its profiles, the only critical system information that remained is the environmental control. The heating and cooling set points and setbacks are defined as 19°C and 21°C respectively. However, the house is heated for the core winter season months of December, January and February. The set

point and setback is considered to be the same depending on their use by DesignBuilder. DesignBuilder uses this information based on the occupancy schedule. The schedule has different occupancy availability at different times throughout the day. DesignBuilder considers set point and setback temperature based on 50% occupancy such that cooling system operates on set point when occupancy is higher than 50% and operates on setback when occupancy is lower than 50% but above 0%. Therefore, DesignBuilder considers the setback as the set point for occupancy schedules below 0.5.

3.2.3 Lighting and Equipment Definition

The lighting system information presented in the previous section is described in terms of total lighting load and lighting power density in watts and watts/m² for each level respectively. However, the inclusion of luminous flux in defining the lighting system not only helps define power requirements but also meets the recommended visual performance. Therefore, this has been taken care in the base model by selecting both as one option. DesignBuilder holds three types of lighting system input requirements based on the type of building being modelled. These include exterior lighting, display lighting, and general lighting. As the base model is a single family dwelling, the display lighting is of least importance and has not been taken into consideration. The exterior lighting is modelled and power requirements have been calculated and supplied. A separate schedule was developed to represent the operation of exterior lighting as shown in **Figure 3.7**.

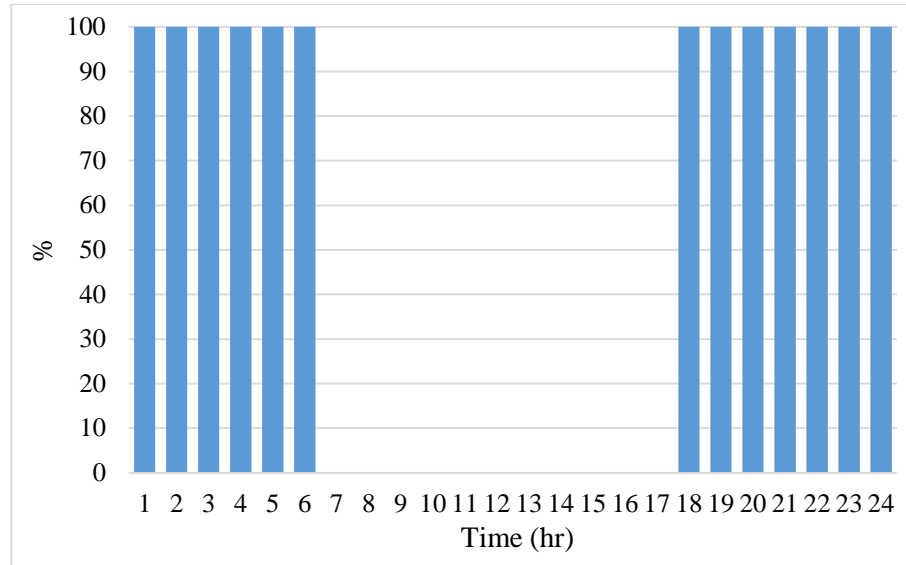


Figure 3.7: Exterior Lighting Schedule

The house was not equipped with any sort of lighting control. Hence, lighting control was not taken into consideration. With respect to general lighting, lighting energy requirements in terms of W/m^2 -100 lux was set and provided for each level. This takes into account power requirements as well as target illuminance level of the lighting. The target illuminance was set to 300 lux and lighting energy for ground and first floors was calculated and set to 2 W/m^2 -100 lux and 1 W/m^2 -100 lux respectively. The assumption that the lighting system for the ground floor is operational for about 35% of the day and 30% for the first floor is taken into consideration. **Table 3.6** discusses appropriate calculations for lighting energy inputs of the model.

Table 3.6: Lighting System Inputs of the Model

Level	Lighting Load (W)	Usage Factor (hr/day)	Target Illuminance (LUX)	Lighting Energy (W/m^2 -100 lux)
Ground Floor	4278	0.35	300	2.43
First Floor	2168	0.30	300	1.26

The equipment definition includes the information pertaining to the heat gained into the zone in terms of load, usage factor and radiant fraction of each equipment. The usage factor for each equipment has been assumed based on the hours of operation per day. **Table 3.7** portrays the heat gained as a result of equipment usage. Relevant information with respect to equipment radiant fraction was taken from 2009 ASHRAE Fundamentals Handbook (ASHRAE Fundamentals, 2009). However, radiant fraction for some equipment were assumed. It was also assumed that the equipment were used only at ground level. After all assumptions and calculations the total heat gain was calculated to be approximately 7 W/m^2 for the ground floor.

Table 3.7: Equipment Usage and Heat Gain

Equipment	Equipment Load (kW)	Usage Factor (hr/day)	Radiant Fraction*	Heat Gain* (W)
Refrigerator	1.00	0.66	0.3	198
Deep Freezer	1.20	0.66	0.3	238
Electric Stove (Cooking Range)	6.00	0.25	0.41	615
Electric Stove Hood (Range Hood)	1.00	0.25	0.25	62.5
Microwave	1.00	0.04	0.24	9.6
Washing Machine	1.20	0.08	0.25	24
Clothes Dryer	5.00	0.08	0.4	160
Vacuum Cleaner	1.10	0.04	0.3	13.2
Hair Blow Dryer	0.90	0.02	0.22	4
TV	0.13	0.25	0.25	8
Coffee Machine	0.90	0.02	0.3	6
Tee Water Boiler	1.10	0.02	0.3	7
Total				1345.3

* Not all data adapted from ASHRAE Fundamentals Handbook 2009 (SI)

3.3 Base Model Validation

Further to the definition of building envelope systems, lighting systems, cooling system, equipment, and other software and model related input parameters, the base model was

simulated for the location of the house. In summary, the annual energy consumption of the house is 162.9 kWh/m². The fuel energy breakdown depicts a percentile share of 5.5% for equipment, 8.4% for general lighting, 80.6% for the cooling system inclusive of fans, 2.4% for heating and 3.1% for exterior lighting as shown in **Figure 3.8**. From the figure it is evident that the major consumer of energy is the cooling system. The cooling energy of the base case house demonstrates agreement with the cooling energy consumption values of 4-bedroom single family residential dwellings of KFUPM. As per the outcomes of the efforts put in to assess building energy use of existing 4-bedroom houses at KFUPM in 2000, the cooling energy consumption share was found to be about 73% of the total energy used (Elhadidy and Ahmad, 2000). The total energy consumption was approximately 193 kWh/m²/annum which is on a higher side in comparison to the base model results. However, the findings represent the construction of building envelope systems such as walls and roof, and efficiency of operation of the cooling system from decade old times of the year 2000 or earlier. Therefore, the need to validate the base model with a valid reasoning was felt for meaningful outcomes.

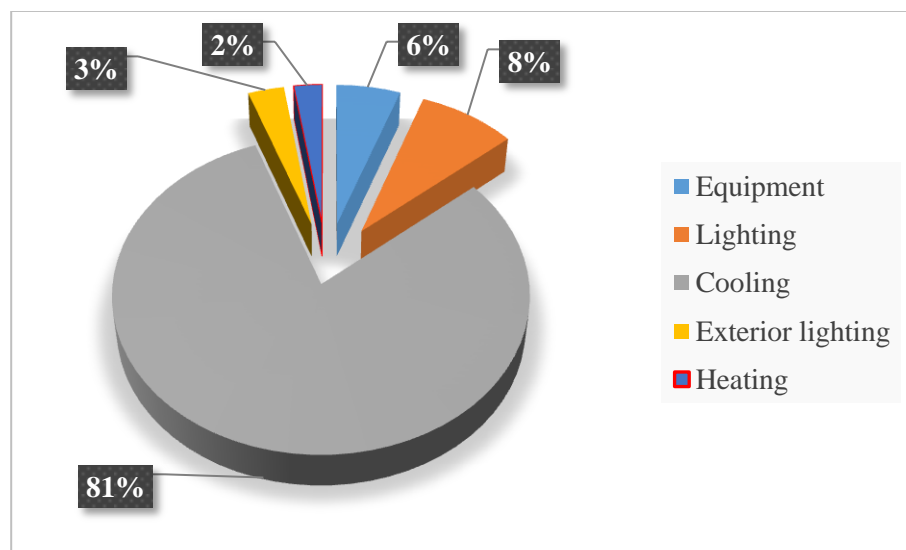


Figure 3.8: Fuel Energy Breakdown of the Base Case Model

3.3.1 Data Recording Setup

With the aim to verify the total energy consumption and to identify the energy flows and end-use patterns, the energy consumption of the newly built 4-bedroom single family housing unit at KFUPM was recorded. Energy meters were prepared, calibrated and set for data recording period and time-steps. A total of three energy meters were used, one to record the total energy use, the other for the house equipment, and the third for HVAC load. The data recording for lighting was not carried out as it was decided to calculate the lighting energy use as a difference of the measured data of HVAC and equipment. This was done to better understand the nexus between the segregated energy flows and end-use patterns of cooling, lighting and equipment in the house. **Figure 3.9** shows the current transformer used to sense the flow of current through the electrical services of the house on the left and the power meter used to record the energy consumption data on the right.

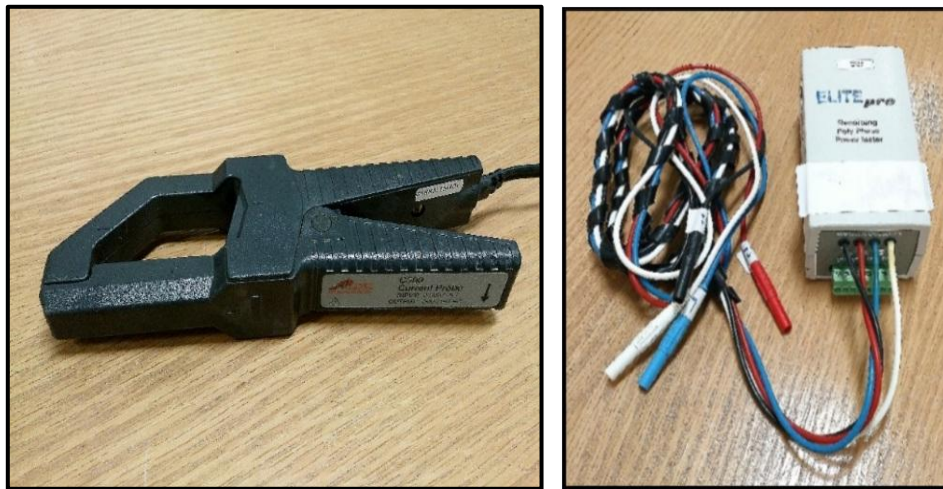


Figure 3.9: Current Transformer (Left) and Poly-Phase Power Monitor (Right)

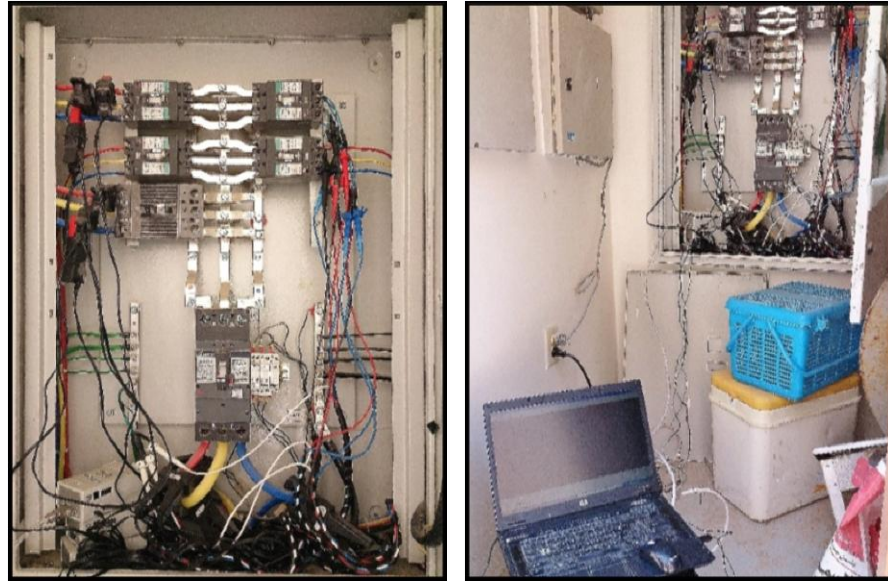


Figure 3.10: Energy Monitor Installed on Electrical Panel Board

The energy monitor was taken to the house and installed in the electrical services room as shown in **Figure 3.10**.

3.3.2 Validation of the Model

The data recording setup was in operation and under observation during the peak summer from July through October for a period of approximately three and half months. This allowed the opportunity to validate the base model with the summer season energy consumption data. As the university's maintenance department had not taken any measures to install energy meters for the housing units, energy monitors had to be installed to measure the energy consumption of the house. Due to time limitations, it was difficult to record the annual energy consumption of the house and group of houses individually for quality control. Thus, the energy consumption of only one house was used for validation. The overall and segregated (cooling, equipment and lighting) energy

consumption values of measurements and base model simulation for the months of July, August and September are presented in **Table 3.8** respectively.

Table 3.8: Total Energy Consumption of the House on a Three Month Basis

	Overall (kWh/m ²)		Segregated (kWh/m ²)					
			Cooling		Equipment		Lighting	
	M	S	M	S	M	S	M	S
July	25.8	24.5	23.7	22.1	1.2	0.8	0.9	1.6
August	28.1	25.2	25.8	22.9	1.3	0.8	1.0	1.6
September	23.8	20.2	21.6	17.9	1.4	0.7	0.8	1.5
Quarterly	77.7	69.9	71.1	62.9	3.9	2.3	2.7	4.7
% Variation	-	10.0%	-	11.5%	-	41.0%	-	74.1%

M = Measured; S = Simulated

From the above table it can be inferred that variation in overall energy end-use of the house is high during the measurement period than the measured values with an increasing percentage variation as each month progresses. The month of July recorded a difference of 5.0% followed by 10.3% for August and 15.1% for September with an overall quarterly variation of 10.0%. Similar observations could be made for the cooling energy end-use statistics. **Figure 3.11** depicts the deviation in the form of scatter plots. Currently, there is possibility of three reasons for this variation. First that the house has many zones with single set-point control in reality and all those zones have not been modelled for simplicity. Dipasquale, et al. (2013) discussed the effect of number of zones on assessment of building loads and conveyed that the building modelled with zones is less prone to variation in energy consumption than the building modelled without the required number of zones. The simplification of zone numbers in simulations can reduce the cooling energy consumption by approximately 20%.

Another possible reason is the exposure of initial portion of supply air and return air ductworks to the outside environment. **Figure 3.1** shows the placement of the cooling systems at first floor level. The supply air ductwork originating from the system travels certain distance before entering the house. Even though the data provided by the Projects Department (KFUPM) do specify insulation of the ductwork, it is believed that there is considerable amount of heat exchange between the supply air and ambient air that has led to increased energy consumption of the house when measured. But this is not at all taken into consideration by DesignBuilder in the simulation model.

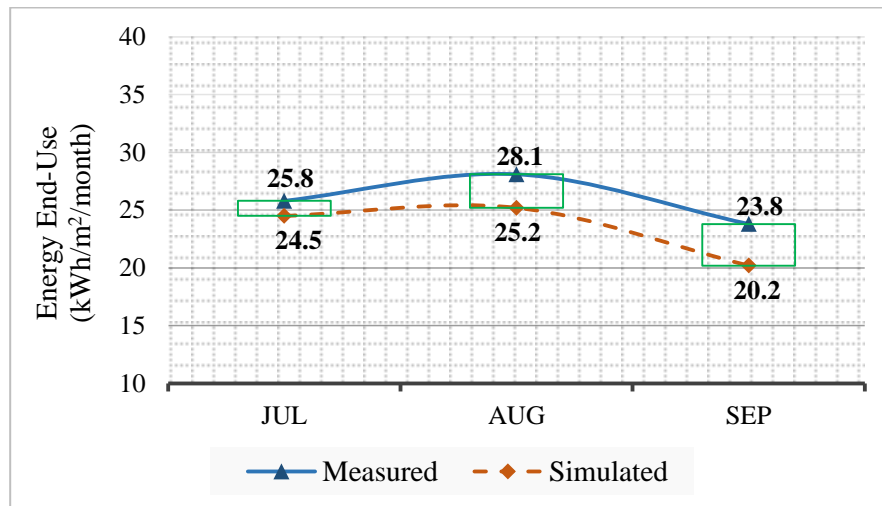


Figure 3.11: Comparison between Measured Energy Consumption and Simulation Results

Figure 3.12 shows the performance line of the house between monthly energy consumption on y-axis and cooling degree days for the year 2012 on x-axis. The y-intercept at x equals zero defines the non-weather dependent energy consumption in terms of distribution and cooling system inefficiencies, and equipment and lighting usage in the house. The value is $3.0 \text{ kWh/m}^2/\text{month}$ and partially represents the energy consumption gap between measured and simulation results.

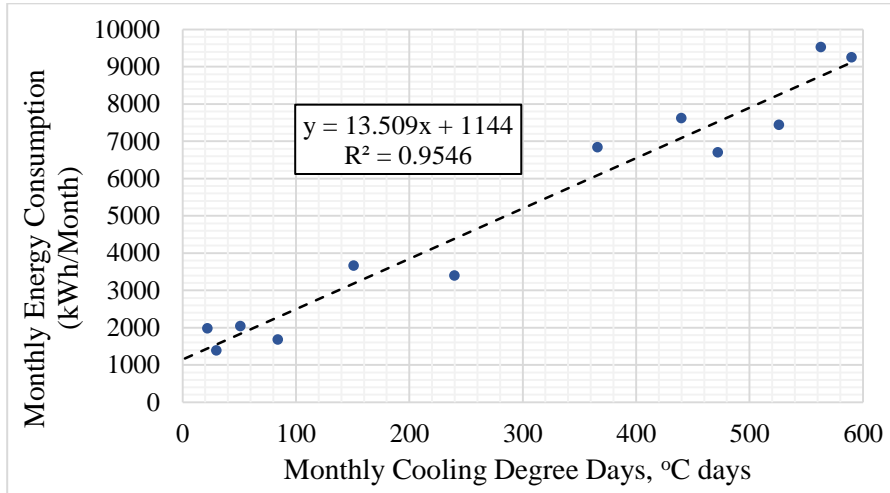


Figure 3.12: Monthly Energy Use to Weather in Dhahran

Subtracting equipment and lighting energy use index gives the distribution and cooling system inefficiencies of about 1.0 kWh/m²/month. This when added to the simulation results of the base case, in addition to the reasoning provided by Dipasquale et al., and as presented in **Table 3.9**, gives the variation between the measured and simulated energy consumption plots. **Figure 3.13** shows the comparison between the two.

Table 3.9: Overall and Cooling Energy Consumption of the House with Inefficient Distribution Systems

	Overall (kWh/m ²)		Cooling (kWh/m ²)	
	M	S	M	S
July	25.8	24.5 + 1.0 + 1.1 = 26.6	23.7	22.1 + 1.1 = 23.2
August	28.1	25.2 + 1.0 + 1.1 = 27.3	25.8	22.9 + 1.1 = 24.0
September	23.8	20.2 + 1.0 + 1.1 = 22.3	21.6	17.9 + 1.1 = 19.0
Quarterly	77.7	76.2	71.1	66.2
% Variation	-	1.9%	-	6.9%

M = Measured; S = Simulated

The inefficiencies of the distribution system in reality are quite high compared to the calculated value of 1.0 kWh/m²/month and give a more realistic variation between the measured and simulated energy consumption when accounted for.

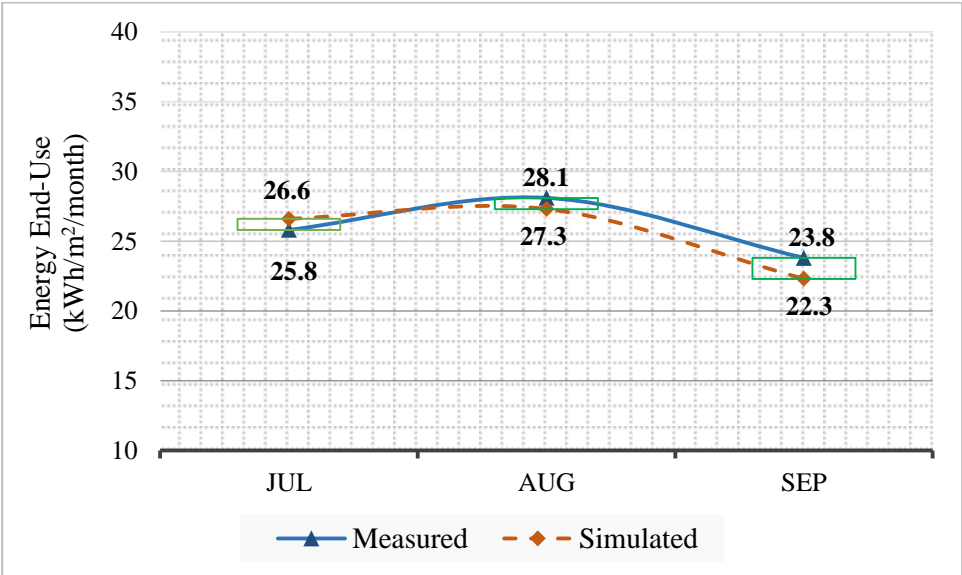


Figure 3.13: Comparison between Measured and Simulated Energy Use w/o System and Distribution Inefficiencies w/ effect of all Zones

CHAPTER 4

ENERGY CONSERVATION STRATEGIES

As described in chapter 2, net-zero energy status is achieved by employing a variety of energy conservation measures in the form of passive design strategies followed by the use of regional / international code and standards, and renewable technologies. This chapter introduces the strategies used in this thesis and presents their individual impact on the total energy use. It also discusses the design elements of solar PV system to meet a specific amount of house load. A total of eight strategies were utilized with five addressing passive design concepts, two addressing code and standard, and finally one addressing renewable energy (PV). **Table 4.1** depicts the strategies used in the research.

Table 4.1: ECMs Toward near-Zero Energy Performance

Type of Strategy	Strategies Employed
Passive Strategies	<ul style="list-style-type: none">✓ Green Roof✓ Double Skin Curtain Wall✓ Pitched Roof✓ Insulating for Thermal Break✓ Exterior Shading
Code / Standard Compliance	<ul style="list-style-type: none">✓ ASHRAE Standard 62.2✓ International Energy Conservation Code (IECC) 2012
Renewable Technology	<ul style="list-style-type: none">✓ Solar PV

4.1 Passive Strategies

4.1.1 Green Roof

Green roof is a passive strategy used to reduce roof heat transfer and improve thermal comfort by providing thermal insulating properties and thermal mass. The EnergyPlus

model of green roof in DesignBuilder requires the green roof to be modelled over the outermost roof layer. The summary of construction features of green roof constructed in the simulation model, as presented in **Table 4.2**, shows the planting media as the outermost layer, over which green roof is modelled. Information pertaining to the thermal and absorptive properties, and design parameters of green roof as inputs are shown in **Table 4.3**.

Table 4.2: Summary of Construction Features of Green Roof

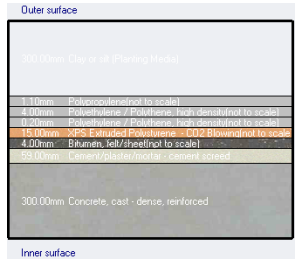
Envelope System Type	Layers (Outside to Inside)	Thickness (m)	U-value (W/m ² -K)	Image
Green Roof	Clay or Silt (Planting Media)	0.03	0.433	
	Polypropylene	0.0011		
	Polyethylene, high density	0.004		
	Polyethylene, high density	0.0002		
	Extruded Polystyrene	0.015		
	Bitumen, felt/sheet	0.004		
	Cement Screed	0.059		
	Reinforced Concrete, cast-dense	0.30		

Table 4.3: Green Roof Model Parameters (DesignBuilder)

	Property	Value
Thermal Bulk Modulus	Thermal Conductivity (W/m-K)	0.20
	Specific Heat (J/kg-K)	1255
	Density (kg/m ³)	1000
Surface Properties	Thermal Absorptance (emissivity)	0.98
	Solar Absorptance	0.60
	Visible Absorptance	0.50
Green Roof Properties	Height of Plants (m)	0.50
	Leaf Area Index (LAI)	5.00
	Leaf Reflectivity	0.40
	Leaf Emissivity	0.95

	Minimum Stomatal Resistance (s/m)	50.0
	Max Volumetric moisture content at saturation	0.50
	Minimum residual volumetric moisture content	0.10
	Initial volumetric moisture content	0.50

The values mentioned in the above two tables have been adopted from appropriate sources in literature. As it was discussed in chapter 2, it is now evident and understandable from the types of green roofing systems that hot and hot-humid climates require intensive type of green roof construction. The intensive the green roof, more the depth required for the growing media (Banting et al., 2005). Therefore, the outermost layer of the green roof known as the planting media is considered to be 0.3 m (approximately 12 inches) deep. A four decade old study interests with respect to the measurement of thermal conductivities of leaves of various species can be found in literature (Hays, 1975). Measurement results indicate mean values of thermal conductivity within the range 0.268 to 0.573 W/m-K. A more recent study of thermo-physical properties of fresh and dry plant leaves revealed thermal conductivity values ranging from 0.27 to 0.5 W/m-K for fresh leaves and 0.21 to 0.48 W/m-K for dry leaves (Jayalakshmy and Philip, 2010). Specific heat ranged from 1255 to 2267 J/kg-K for fresh leaves and 1514 to 5174 J/kg-K for dry leaves. Similarly, mass density of fresh leaves was measured to be in the range 475 to 918 kg/m³ with a slight variation in values for dry leaves 336 to 747 kg/m³. The height of plants and LAI have been assumed to be 0.5 m and 5.0 respectively based on the hot-humid climate of Dhahran. The maximum irrigation rate for the site green roof is considered equivalent in terms of depth of growing media per hour.

The remaining surface and green roof properties are assumed based on the input output reference of EnergyPlus.

Besides all benefits it can offer, a green roof can as well provide thermal insulating properties in terms of increased thermal mass and reduced heat island effect which reduces the need for roof thermal insulation. Castleton highlighted the situations in which greatest energy savings could be achieved using green roof (Castleton et al., 2010). It was found that green roofs are most effective with poorly insulated roof structures. Buildings with high amounts of roof insulation hardly demonstrated annual energy end-use reduction with green roofs. This conveys that buildings be either uninsulated or poorly insulated. Therefore, green roof for the current house model was assumed to be poorly insulated with just 0.015 m of thermal insulation as a standard practice.

4.1.2 Double Skin Curtain Wall

The idea facilitating energy performance improvement and thermal comfort enhancement by ventilating the building envelope systems could be seen in the ADAE strategy. Mentioned in the literature in chapter 2, ADAE strategy provides the feasibility of actively ventilating the air within the envelope cavities to reduce heat gain into the zone. Double skin curtain wall is a similar strategy but focuses only on one envelope system, unlike ADAE. The double skin façade model of DesignBuilder allows the modelling of a double skin ventilated façade system. The only difference observed for the strategy under investigation is the presence of the wall as the building skin instead of a façade. **Figure 4.1** shows the construction of the double skin curtain wall system with a cavity within. As the house has an aspect ratio of approximately 1:1.5, the south side of the house provided the feasibility to create a cavity within the envelope to assess the impact of double skin

curtain wall system on energy performance. Glazing units on the south walls for both the floors were modelled appropriately. The width of the cavity, 0.3 m, has been taken from literature (Wong et al., 2008). Other parameters and considerations for model simulation have been selected as required.

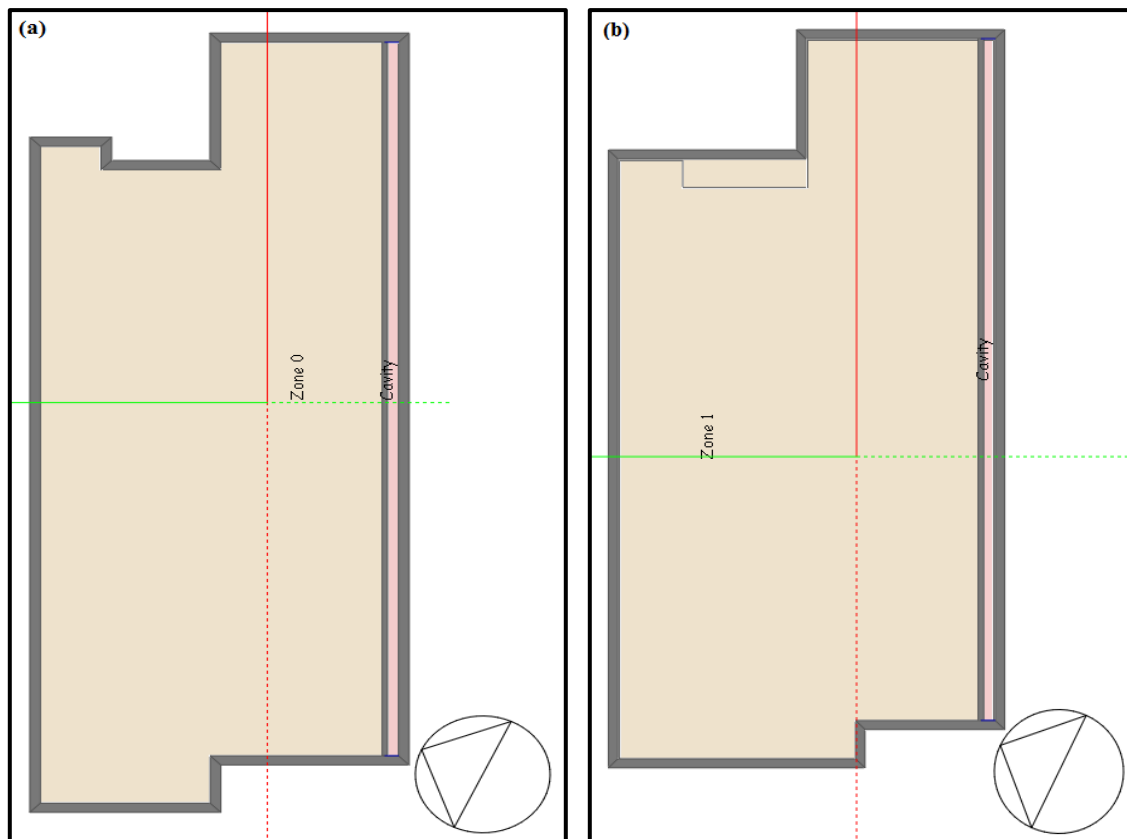


Figure 4.1: Double Skin Curtain Wall System (a) Ground Floor, (b) First Floor

4.1.3 Pitched Roof

Horizontal roofing systems have always been the source of huge amounts of heat gain into the building, especially, in hot climates. Unlike walls and other building envelope systems, the roof is exposed to solar radiation most of the time throughout the day. The direct solar beam and the amount of heat gain could be avoided simply by enhancing the roof geometry and tilting it at a certain angle. This enhancement known as pitched roofing

system can as well be fruitful when solar radiation utilization is in question. Besides reducing heat gain in contrast to the horizontal roof, pitched roof helps yield electricity by harnessing solar radiation when appropriately tilted at a certain angle based on the latitude. DesignBuilder provides the feasibility of modelling pitched roof over horizontal roof with the help of various tools and features. **Figure 4.2** represents the construction of the pitched roof.

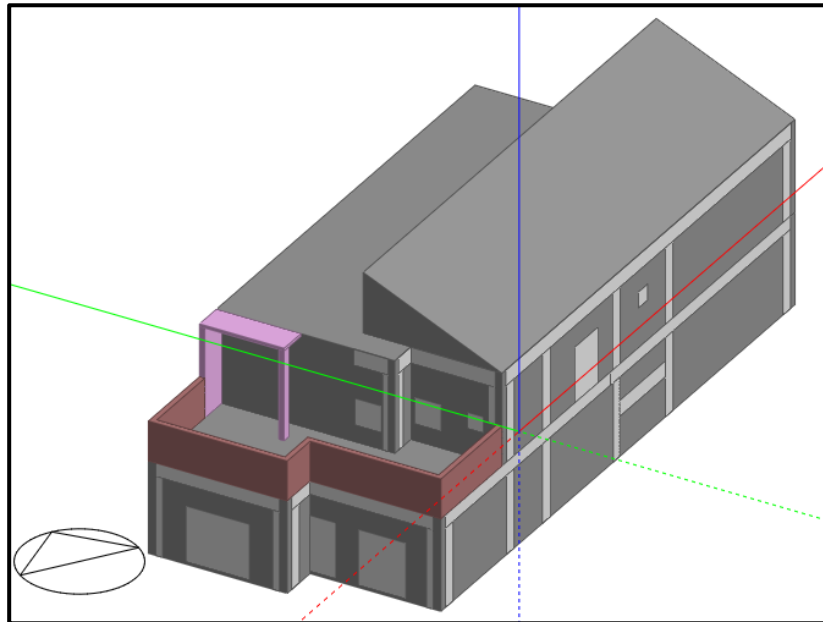


Figure 4.2: Pitched Roof Construction


The arrangement in the figure above demonstrates the limits of pitched roof on horizontal roof area. This area has been selected for four genuine reasons. Firstly, the horizontal roof surface has unusual perimeter. The second reason that the selected side of the horizontal roof is higher in area which gives the possibility of more electricity production as a result of solar PV. Thirdly, the remaining horizontal portion of the horizontal roof is considered to be green roof. This would otherwise shade part of the pitched roof, i.e. PV system, and cause hindrance in the production of the required amount of electricity. The fourth reason

that the present arrangement shades the other portion of the roof thereby reducing heat gain into the zone. The numerical measure of steepness in the form of tilt angle for pitched roof was calculated for the latitude of Dhahran. The parametric considerations of pitched roof have been selected as required based on the inputs requirement and modelling capability of DesignBuilder.

4.1.4 Insulation for Thermal Break

Chapter 3 described and introduced to the development of the base case model of the house. Emphasised in the section 3.2.1 was the occurrence thermal bridging in the house and the concept of sub-surface construction capability of DesignBuilder. As mentioned earlier, sub-surface is an anomaly to the actual construction of the surface and provides the feasibility of modelling thermal bridging through walls, partitions and pitched roof. It effectively models the heat flow through any of the structural elements of the building. **Figure 3.4** demonstrates the placement of sub-surface in the geometric model. For the present base case model, the wall specification at the points of location of columns and beams exposed to the outside environment is different in comparison to the actual wall specification. This depicts real life conditions to the heat gains into the zone. **Table 4.4** shows the specifications and construction features of sub-surface.

Table 4.4: Construction Features and Specifications of Sub-Surface Wall

Envelope System Type	Layers (Outside to Inside)	Thickness (m)	U-value (W/m ² -K)	Image
Sub-surface	Plaster, dense	0.016	2.29	
	Concrete Block, heavy	0.25		
	Plaster, lightweight	0.013		

As the structure of a building consists of columns and beams along the building envelope, sub-surface construction represents a solid concrete structure and divides the wall system into distinct discontinuous elements. This way the envelope establishes thermal break in the simulation model. It would then be interesting to see the effect of thermally insulating the envelope on energy end-use reduction as a result of evaded thermal bridging. Thus, an extra thin layer of thermal insulation was added toward the exterior of the wall mass. The idea behind placing the thermal insulation toward the exterior is to avoid the transfer of heat at the first surface of contact of the columns and beams. The strategy not only reduces heat transfer but also inhibits the potential of heat being stored in the wall mass. This does not allow the thermal bridging elements to re-radiate the stored heat during off-sunshine hours in summer. The construction features of the modified wall system could be observed in **Table 4.5**.

Table 4.5: Construction Features and Specifications of Modified Wall

Envelope System Type	Layers (Outside to Inside)	Thickness (m)	U-value (W/m ² -K)	Image
Wall (Modified)	Plaster, dense	0.016	0.466	
	Extruded Polystyrene	0.02		
	Concrete Block, medium	0.10		
	Extruded Polystyrene	0.03		
	Concrete Block, medium	0.10		
	Plaster, lightweight	0.013		

4.1.5 Exterior Shading

Exterior shading is a strategy of reducing the heat gain into the zone by controlling the incidence of solar radiation on indoor environment. This could be done by incorporating external shading elements into the building geometry. Various studies could be found in

literature that illustrate the importance of exterior shading devices in terms of reduced heat gains. One such study was conducted in the form of a series of parametric studies on a residential building for all orientations by considering three horizontal external shading dimensions for three different window-to-wall ratios (Liping and Hien 2007). As a result, the strategy employed reduced energy consumption. It was also found that the shading dimensions of 0.6 and 0.9 m were more effective in providing thermal comfort.


For the present base case model, it was observed that no exterior shading element was designed for the house. Cited in literature was the study carried out by Ernest Orlando Lawrence Berkeley National Laboratory that provided guidelines on an integrated approach to cost-effective design of perimeter zones (O'Connor et al., 1997). This included the design of exterior overhangs as a function of solar angles and window dimensions. The following equation was used to design the depth of exterior overhang:

$$h = \frac{D \times \text{Solar Altitude}}{\cos(\text{Solar Azimuth} - \text{Window Azimuth})} \quad (4.1)$$

The height and depth of the shade are given by h and D respectively, and the height of the shade was assumed to be same as the height of the window glazing. Core day of the cooling season, i.e. July 21, and solar time 10:30 AM were the assumptions under consideration to determine the solar angles. Calculations were performed for *hour angle*, *declination angle*, *solar altitude*, *solar azimuth* and *surface azimuth*. The solar altitude and solar azimuth were calculated to be 68.6° and 79.34° respectively. Four different values for surface azimuth were calculated based on the orientation as shown in **Table 4.6**. The depths of exterior overhang at various orientations are dependent on the depth of

shade for each glazing unit. Therefore, overhang with the highest depth for each orientation has only been tabulated.

Table 4.6: Surface Azimuth and Depth of Overhang for Various Orientations

	North	South	East	West
 Literature	180°	0°	-90°	90°
Base Case Model	$180 - 25 = 155^{\circ}$	$0 + 25 = 25^{\circ}$	$90 - 25 = 65^{\circ}$	$90 + 25 = 115^{\circ}$
Depth of Overhang (m)	0.12	0.69	0.84	0.7

4.2 Compliance with Code and Standard

4.2.1 ASHRAE Standard 62.2

ASHRAE standard 62 is a voluntary set of guidelines by the Approved American National Standard for ventilation and acceptable indoor air quality for both commercial and residential buildings. As the title goes, ASHRAE standard 62.2 is intended for single- or multi- family low-rise residential dwellings. The standard defines minimum required amounts of mechanical and natural ventilation (ASHRAE Standard 62.2, 2007). Separate ventilation air requirements based on floor area and number of bedrooms are provided by the standard to provide whole-building natural or mechanical ventilation as shown in **Table 4.7**. The gross floor area of the base case house is approximately 377 m^2 with more than 7 rooms when whole building is considered. This gives an approximation of the outside air requirement of 57 L/s. Similarly, the outside air requirements for both ground and first floors have been found to be 35 L/s from the standard.

Table 4.7: Ventilation Air Requirements in L/s (ASHRAE Standard 62.2, 2007)

Floor Area (m ²)	Bedrooms				
	0-1	2-3	4-5	6-7	>7
< 139	14	21	28	35	42
139.1 - 279	21	28	35	42	50
279.1 - 418	28	35	42	50	57
418.1 - 557	35	42	50	57	64
557.1 - 697	42	50	57	64	71
> 697	50	57	64	71	78

The outside air definition method of the base case model for mechanical ventilation in DesignBuilder is by zone requirements. This value has been set based on the HVAC system specifications for both ground and first floors. The ventilation air requirements approximated based on ASHRAE standard 62.2 were provided as input to DesignBuilder in terms of L/s-person, and the outside air definition method was changed from zone option to minimum fresh air per person. The ventilation air requirements calculated for the house and its zones based on ASHRAE standard 62.2 is 5 L/s-person for both ground and first floors.

4.2.2 International Energy Conservation Code (IECC)

The International Energy Conservation Code 2012 was used to enhance the thermal specifications of the building envelope. Envelope systems such as walls, roof, floor and windows were checked for compliance with the code. IECC represents mandatory set of requirements in the form of a comprehensive guide for commercial and residential buildings to achieve minimum, required, and much needed levels of energy efficiency. The cooling degree days for a specific location aid in the identification of climatic zone which would then be used to know the thermal requirements of different building envelope systems. **Table 4.8** portrays the U-values of each system and compares it with

the U-values of the corresponding systems as specified by the International Energy Conservation Code 2012.

Table 4.8: Thermal Specifications of Envelope Systems of Base Case vs IECC 2012

Envelope System Type	U-value (W/m ² -K)		Envelope System Enhancements
	IECC 2012	Base Case	
Wall	1.89	0.466	✗ Not required
Roof	0.189	0.539	✓ Required
Window	2.839	2.709	✗ Not required
Floor	0.437	0.792	✓ Required

From the above table it can be seen that the roof and floor systems have U-value higher than the prescribed IECC 2012 requirements. Thus, these systems are improved thermally based on the presence of construction elements in them. The ground floor of the base case model isn't equipped with thermal insulation at all. The roof does have insulation but fails to meet the prescribed IECC 2012 requirements. Hence, a layer of thermal insulation is added to the ground floor and roof is replaced by a massive one with low U-value based on the supporting literature (Al-Saadi and Budaiwi, 2007). Thermal specifications of windows on the other hand did not show any prospect for improvement for a couple of reasons. Firstly, they already meet the IECC 2012 fenestration requirements. Secondly, the WWR for the house is calculated to be 0.1 which is too less for convincing outcomes. But the wall system definitely showed scope for improvement in spite of meeting the IECC 2012 mass wall requirements. The idea of satisfying the code and taking a step further and improving the system performance by approximately 10% does make a difference.

Table 4.9: Summary of Enhanced Construction Features of Building Envelope Systems

Envelope System Type	Layers (Outside to Inside)	Thickness (m)	U-value (W/m ² -K)	Image
Wall (Modified)	Plaster, dense	0.016	0.466	
	Extruded Polystyrene	0.02		
	Concrete Block, medium	0.10		
	Extruded Polystyrene	0.03		
	Concrete Block, medium	0.10		
	Plaster, lightweight	0.013		
Roof (Replaced)	Concrete Tiles, roofing	0.04	0.183	
	Cement Mortar	0.05		
	Sand and gravel	0.025		
	Polyethylene, high density	0.004		
	Polyurethane Board	0.10		
	Concrete, cast-foamed	0.10		
	Reinforced Concrete, cast-dense	0.20		
Floor (Modified)	Ceramic Tiles, glazed	0.01	0.41	
	Cement Mortar	0.01		
	Extruded Polystyrene	0.04		
	Reinforced Concrete, cast-dense	0.125		
	Polyethylene, high density	0.002		
	Earth, gravel	0.5		

This strategy definitely proves worthy for the base case model with thermal bridging through columns and beams along the envelope construction. The enhanced envelope systems construction features are presented in **Table 4.9**. The modified wall system is the same as the one discussed in section 4.1.4.

It was only after the successful replacement of the roof system that its feasibility was studied in comparison to green roof for implementation in the house model. Though the replaced roof system meets IECC 2012 requirement, it still falls under the umbrella of traditional building practices. Where IECC is prescriptive yet mandatory requirement, green roof is innovation as well as a step further toward sustainability. This was the major reason for considering green roof over IECC 2012 compliant roof insulation level. But the

reasoning fails to impress upon viewing the U-value of both roofs as mentioned in **Table 4.2** and **Table 4.9**. Therefore, simulation runs of both roof systems and literature review helped better understand and comment on the effect of each strategy on energy performance of the house. Results are tabulated in **Table 4.10**.

Table 4.10: Annual Energy Performance

	Energy End-Use (kWh/m ² /annum)	Annual Energy Savings
Base Case	162.9	-
Green Roof	154.6	5.1%
IECC 2012 Compliant Roof	159.9	1.8%

From the above table it is clear that green roof is more energy efficient than IECC 2012 compliant roof. This is due to the fact that green roof has thermal mass in the form of soil substrate on the roof. The thicker the soil layer, the better the roof performs and reduces heat gain or loss. Moisture content of the soil does have an impact on the heat lost to ambient air through evapotranspiration (Castleton et al., 2010). High rates of evapotranspiration draw heat out of a building as a result of wetness in soil substrate. Evapotranspiration is the process of evaporation and transpiration where water present in the soil evaporates in the form of vapour and at the same time transpires through the leaves. The IECC roof on the other hand too reduced cooling energy but could not quite perform as green roof due to the absence of evapotranspiration. Another reason behind better performance of green roof as pointed in a research study is the albedo (Gaffin et al., 2010). Castleton et al. defined albedo as the ratio of total reflected to incident electromagnetic radiation. The higher the albedo, the better. According to Gaffin et al., albedo of green roof is comparable to that of the whitest roof with values ranging from 0.7 to 0.85. Conventional roofs have an albedo of 0.1 to 0.2. Besides all this, green roofs

address sustainability by providing biodiversity, storm water retention and quality, improved acoustical performance, etc.

4.3 Renewable Energy

4.3.1 Solar Photovoltaic (PV)

This section represents the last of the strategies in reducing the energy demand of the house in terms of dependence on electricity grid by addressing electricity production through PV. Relevant sources in literature have discussed the energy end-use of residential dwellings and established an understanding that cooling energy is dominant and accounts for approximately 73% of the total house load. Similar statistics could be observed for the base case model in section 3.3 where cooling energy shares around 79% of the total energy end-use. The remaining energy is shared by equipment, general lighting and exterior lighting.

Table 4.11: Average Representative Day of Each Month Depicting Energy End-Use

Day of Month	Room Electricity (kWh)	General Lighting (kWh)	Exterior Lighting (kWh)	Total (kWh)
Jan 17	9.2	14.3	5.2	28.7
Feb 16	9.3	13.6	5.2	28.1
Mar 16	9.3	13.6	5.2	28.1
Apr 15	9.2	14.3	5.2	28.7
May 15	9.2	14.3	5.2	28.7
Jun 11	9.2	14.3	5.2	28.7
July 17	9.2	14.3	5.2	28.7
Aug 16	9.3	13.6	5.2	28.1
Sep 15	9.2	14.3	5.2	28.7
Oct 15	9.2	14.3	5.2	28.7
Nov 14	9.2	14.3	5.2	28.7
Dec 10	9.2	14.3	5.2	28.7

Thus, at least meeting the remainder of the energy through solar PV to offset the grid dependence for this part of the house load was found a viable option. **Table 4.11** shows the simulation results of energy end-use of equipment and lighting for an average day, representative of each month (Duffie and Beckman, 2013).

The segregated energy end-use per representative day is similar for each month in question as per the simulation output of DesignBuilder. Therefore, solar PV need to be designed to meet the total energy end-use of 28.7 kWh/d to offset the daily load from the utility for energy conservation and grid demand reduction. A methodology to size and cost PV system and its components was presented (Chel et al., 2009). Utilized were simple mathematical expressions, and information such as daily electrical load of 9 kWh/d, tilt angle equivalent to latitude and number of sunshine hours. The methodology presented PV system sizing for both stand-alone off-grid PV and BIPV systems, and seemed applicable to locations all over the world. A 2.32 kW_p PV system was found suitable for the operation of the given daily electrical load requirement. The following steps discuss the procedure to calculate the land area requirements based on the availability of solar resource and worst scenario for PV system to meet the daily electricity load.

4.3.1.1 Determination of Daily Energy Requirements

The first step in PV system design is to determine the electrical load the system has to meet each day. The details of the total electrical load of 28.7 kWh/d have been shown in **Table 4.11**. Therefore,

$$\text{Daily energy requirement} = \mathbf{28.7 \text{ kWh/d}} \quad (4.2)$$

4.3.1.2 Determination of System Design Load

The design load is the increased value of the load based on the efficiency of the system. It is calculated as follows:

$$\text{Design electrical load } (E_D) = \frac{\text{Daily Energy Requirement}}{\eta_{PV \text{ System}}} \quad (4.3)$$

where; $\eta_{PV \text{ System}}$ is efficiency of PV system and is given as a function of efficiencies of PV in regard to maximum power point (MPP) output, inverter, charge controller, battery and distribution cables.

$$\eta_{PV \text{ System}} = \eta_{PV \text{ MPP}} \times \eta_{inv.} \times \eta_{cc} \times \eta_{batt.} \times \eta_{dis.} = 0.6 \quad (4.4)$$

$$\therefore E_D = \frac{28.7}{0.6} = \mathbf{47.8 \text{ kWh/d}}$$

where; $\eta_{PV \text{ MPP}}$ is efficiency of PV panel with regard to its MPP output, $\eta_{inv.}$ is efficiency of inverter, η_{cc} is efficiency of charge controller, $\eta_{batt.}$ is efficiency of battery and $\eta_{dis.}$ is efficiency of distribution cables.

4.3.1.3 Solar Radiation Needed

This depicts the amount of solar radiation needed to meet the daily energy requirement. It is a function of PV conversion efficiency and is calculated as follows:

$$\text{Solar radiation needed } (E_{\text{Solar Rad.}}) = \frac{E_D}{\text{PV panel conversion efficiency}} \quad (4.5)$$

$$\therefore E_{\text{Solar Rad.}} = \frac{47.8}{0.15} = \mathbf{318.7 \text{ kWh/d}}$$

4.3.1.4 Land Area Requirements

The land requirements represents minimum area required for PV system to produce and meet the electricity needed for a day. This will later help in determining the size of PV array. Area required is a function of daily solar radiation incident at a particular location.

Figure 4.3 shows daily global horizontal radiation for each month for Dhahran.

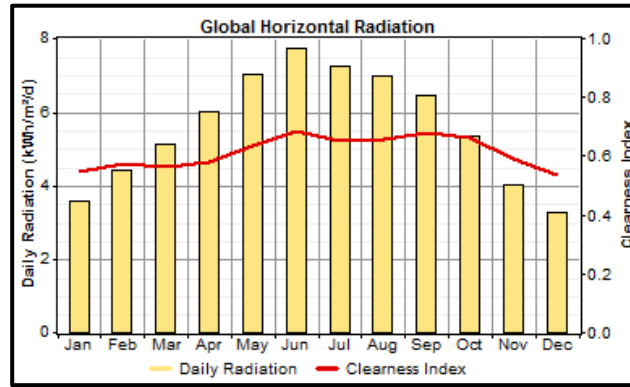


Figure 4.3: Daily Global Horizontal Radiation for Dhahran (HOMER)

The solar radiation data was obtained from NASA surface meteorology and solar energy website (NASA SSE, 2013). From the figure it can be observed that maximum radiation is incident in June and minimum in December. For the worst scenario, lowest amount of daily solar radiation is considered for year-round use. System meeting the daily energy requirements on an average representative day in December will surely meet the same when the solar radiation is higher during the rest of the months.

$$\therefore \text{Area required} = \frac{E_{\text{Solar Rad.}}}{\text{Daily Solar Radiation}} = \frac{318.7}{3.28} = \mathbf{97.2 \, m^2} \quad (4.6)$$

Therefore, an area of 97.2 m² is required to successfully satisfy the equipment and lighting load of 28.7 kWh/d when a PV panel with conversion efficiency of 15% is used.

However, PV technology and power output (Wp) of PV module can greatly impact on area.

4.3.2 PV System Design

This section systematically discusses the design of PV system in HOMER based on equipment and lighting loads of the base case model, tilt angle, solar resource availability and system costs. As described in chapter 2, HOMER is a hybrid micro-power optimisation model that carries out a number of sensitivity analyses and identifies cost-effective solutions to energy requirements. Various research initiatives could be found in literature using the software. A study on performance analysis of hybrid PV/diesel energy system under Malaysian conditions was carried out using HOMER (Lau et al., 2010). Another feasibility study was conducted to replace the diesel generators with wind farms, PV and hydrogen production systems using HOMER (Giatrakos et al., 2009). Research engineers at Center for Engineering Research at KFUPM presented their findings on economic analysis of hybrid power systems for residential loads in hot climates (Shaahid and Elhadidy, 2008). Application of gen-sets in small solar power systems was as well carried out to meet a certain amount of daily load using HOMER (Givler and Lilienthal, 2005). The detailed input information to be modelled in HOMER is identified as primary loads and system components. While the former represents the load to be met by the renewable energy system, latter characterises the associated components such as PV, converter and battery.

4.3.2.1 Primary Load & Solar Resource

As discussed in the earlier section in **Table 4.11**, daily energy requirements in terms of electrical loads were found to be 28.7 kWh. HOMER provides the feasibility to input the

daily profile of the load for each month. Hence, hourly simulation results of a day were supplied to the HOMER model. **Figure 4.4** depicts the daily load profile. The load profile information is used by the model to generate a scaled annual average (kWh/d) value that represents the average of all the annual loads on a daily basis. The calculated equipment and lighting load of 28.7 kWh/d approximately matched with the scaled annual average value in the model.

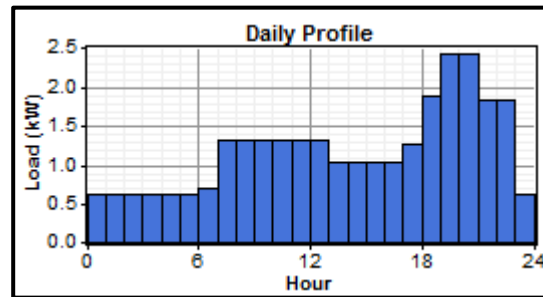


Figure 4.4: Daily Load Profile (HOMER)

Also presented in previous section was solar resource input information for Dhahran in terms of daily global horizontal radiation. It was obtained from NASA surface meteorology and solar energy website and presented in **Figure 4.3**.

4.3.2.2 PV Array

Information with respect to PV array sizing includes cost of the array, lifetime, slope, azimuth, derating factor, ground reflectance and temperature effects. The cost for 1 kW of output was considered to be \$5000 (Feldman et al., 2012). This includes shipping, tariffs, installation, and dealer mark-ups. The array was assumed to function for a lifetime of 25 years. Slope of the array was approximated using the latitude of Dhahran and set as 23.7° (Rakovec et al., 2011). A study on optimum PV tilt angle was carried out for the latitude of Madinah (Benghanem, 2011). The optimum tilt angle was found to be different throughout the year and average tilt angle yielded a slope slightly less than the latitude.

The study concluded yearly average panel tilt angle of 23.5° in comparison to the 24.5° latitude of Madinah. Derating factor for PV is the scaling applied by the software to take into consideration the reduced output as a result of shading, dust, snow cover, etc. The value of 0.9 was assumed which means the array output is 10% less than actual. The effect of temperature on array defines how the maximum power varies with cell temperature. Hence, site dry bulb temperature data was supplied to the model. Capacities of different PV panel variations were considered in the analysis. **Figure 4.5** shows all PV array input data in the model window.

PV Inputs

File Edit Help

Enter at least one size and capital cost value in the Costs table. Include all costs associated with the PV (photovoltaic) system, including modules, mounting hardware, and installation. As it searches for the optimal system, HOMER considers each PV array capacity in the Sizes to Consider table.

Note that by default, HOMER sets the slope value equal to the latitude from the Solar Resource Inputs window.

Hold the pointer over an element or click Help for more information.

Costs

Size (kW)	Capital (\$)	Replacement (\$)	O&M (\$/yr)
1.000	5000	0	0

{.} {.} {.}

Properties

Output current: ☐ AC ☒ DC

Lifetime (years): 25 {.}

Derating factor (%): 90 {.}

Slope (degrees): 23.7 {.}

Azimuth (degrees W of S): 0 {.}

Ground reflectance (%): 20 {.}

Sizes to consider

Size (kW): 0.000, 8.100, 8.200, 8.300, 8.400, 8.500, 8.600

Cost Curve

Cost (000 \$) vs Size (kW)

— Capital — Replacement

Advanced

Tracking system: No Tracking

☒ Consider effect of temperature

Temperature coeff. of power (%/°C): -0.5 {.}

Nominal operating cell temp. (°C): 47 {.}

Efficiency at std. test conditions (%): 15 {.}

Help Cancel OK

Figure 4.5: PV Array Input Data Requirements of HOMER

4.3.2.3 Batteries

Batteries are used to store electricity produced by PV panels. The model input data requires the cost of battery, number of strings and batteries per string. Trojan L16P battery was considered with 24 V as voltage and 360 Ah as the capacity. The cost was assumed to

be \$300 per battery based on literature research. Operation and maintenance was assumed to be \$10 every year. Battery sizing is the most critical part of system design as bus voltage affects the performance of and interaction between other systems such as array and inverter. Different number of batteries were considered for the model to optimally choose from. **Figure 4.6** shows the battery inputs of the model.

Battery Inputs

File Edit Help

Choose a battery type and enter at least one quantity and capital cost value in the Costs table. Include all costs associated with the battery bank, such as mounting hardware, installation, and labor. As it searches for the optimal system, HOMER considers each quantity in the Sizes to Consider table.

Hold the pointer over an element or click Help for more information.

Battery type: **Trojan L16P** Details... New... Delete

Battery properties

Manufacturer: Trojan Battery Company
Website: www.trojan-battery.com

Nominal voltage: 6 V
Nominal capacity: 360 Ah (2.16 kWh)
Lifetime throughput: 1,075 kWh

Costs

Quantity	Capital (\$)	Replacement (\$)	O&M (\$/yr)
1	300	250	10.00
	(.)	(.)	(.)

Advanced

Batteries per string: 4 (24 V bus)
☐ Minimum battery life (yr): 4 (.)

Sizes to consider

Strings: 0, 10, 11, 12, 13, 14, 15, 16, 17

Cost Curve

Cost (000 \$) vs Quantity

Legend: Capital (red line), Replacement (blue line)

Figure 4.6: Battery Input Data Requirements (HOMER)

4.3.2.4 Inverter

Any PV system will have an inverter underneath. Inverter is intended to convert the DC electricity of PV to AC for household application. Like other systems, one of the inputs for inverter is the cost for 1kW power output. A capital cost of \$900 per kW was considered assuming that it does not require any sort of maintenance. The efficiency is 90% and lifetime 15 years. Capacity variations from 3.5 kW to 4.5 kW were supplied to the model as shown in **Figure 4.7**.

Converter Inputs

File Edit Help

☒ A converter is required for systems in which DC components serve an AC load or vice-versa. A converter can be an inverter (DC to AC), rectifier (AC to DC), or both.

Enter at least one size and capital cost value in the Costs table. Include all costs associated with the converter, such as hardware and labor. As it searches for the optimal system, HOMER considers each converter capacity in the Sizes to Consider table. Note that all references to converter size or capacity refer to inverter capacity.

Hold the pointer over an element or click Help for more information.

Size (kW)	Capital (\$)	Replacement (\$)	O&M (\$/yr)
1.000	900	600	0
{.}	{.}	{.}	{.}

Sizes to consider

Size (kW)

0.000
3.500
3.600
3.700
3.800
3.900
4.000

Cost Curve

Cost (\$)

Size (kW)

Capital Replacement

Inverter inputs

Lifetime (years) 15 {.}

Efficiency (%) 90 {.}

☒ Inverter can operate simultaneously with an AC generator

Rectifier inputs

Capacity relative to inverter (%) 100 {.}

Efficiency (%) 85 {.}

Help Cancel OK

Figure 4.7: Inverter Input Requirements of HOMER

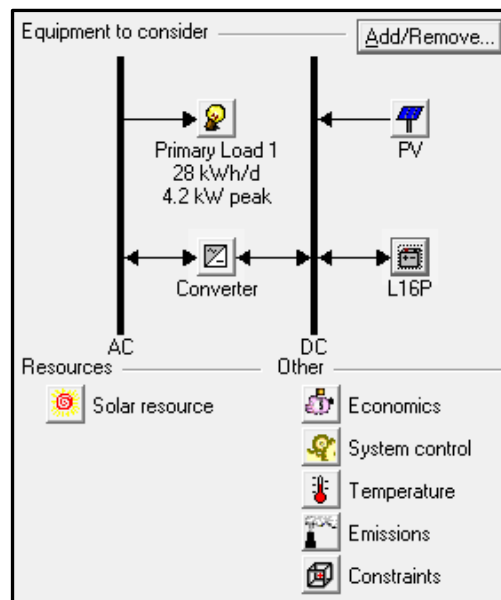


Figure 4.8: Schematic Representation of the Proposed Renewable System

Wide variety of information ranging from one type of system to other was supplied to the model. Slope was set to 23.7° facing due south. Temperature effects and derating factor too were considered in the model to reflect the real-world situations in harnessing solar

radiation for clean energy. Besides the cost of all systems, replacement cost was also accounted as it applies once the system's lifetime is complete. The model at this stage would consider the replacement cost as a measure for the new component. This completed the development of renewable energy model for the current phase of study as shown in **Figure 4.8**. Technical data assumed for the system components is presented in **Table 4.12**.

Table 4.12: Technical Data for Selected System Components

Description	Data
PV	
Sizes	8.1-9.5 kW
Capital Cost	\$ 5000/kW
Lifetime	25 years
Derating Factor	0.9
Slope	23.7°
Inverter	
Sizes	3.5-4.5 kW
Capital Cost	\$ 900/kW
Replacement Cost	\$ 600/kW
Lifetime	15 years
Efficiency	90%
Battery	
Type	Trojan L16P
Nominal Voltage (4 batteries per string)	24 Volts
Nominal Capacity	360 Ah
Capital Cost	\$ 300/battery
Replacement Cost	\$ 250/battery
Operating & Maintenance Cost	\$ 10/year

Optimisation results of the model show the following system architecture for the daily equipment and lighting load of the base case house model: **8.7 kW PV with 56 Trojan L16P batteries and a 4.1 kW inverter**. **Figure 4.9** represents 3-D sun path diagram of nZEB model depicting roof slope and extended surfaces to house PV panels.

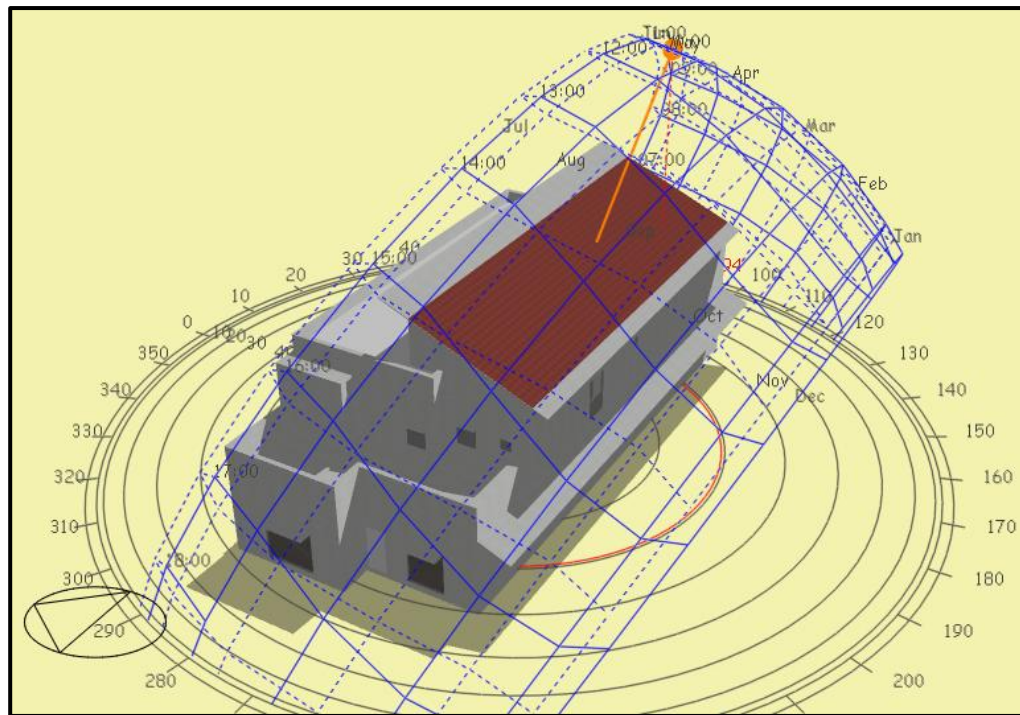


Figure 4.9: 3-D Sun Path Diagram of nZEB Model

CHAPTER 5

RESULTS ANALYSIS AND DISCUSSION

The thesis so far has seen the development and verification of the base case model and an exhaustive discussion of all the strategies utilized to achieve near-zero energy status. The initial phase of the current chapter focuses on the base case model and investigates its performance for energy end-use and thermal comfort. This is followed by a brief overview of the impact of each strategy on energy performance of the house. Finally, the chapter aims to discuss the implementation of all strategies to the base case model and evaluate the new design for energy performance and thermal comfort of occupants. Results of base case and new design are then associated and comments are provided with valid and appropriate reasoning.

5.1 Performance Evaluation of Base Case

The developed and verified base case model of single family 4-bedroom university faculty housing was simulated using state-of-the-art DesignBuilder simulation program. Annual simulation was performed using the weather data file of Dhahran for the year 2012. Results of annual energy consumption for each month are shown in **Figure 5.1**. A total of 162.9 kWh/m² of energy is consumed by the base case model annually. It can be observed that August recorded a monthly high of 25.2 kWh/m² and February with a low 3.7 kWh/m². Literature cites various techniques to evaluate the energy performance of a building. Different indicators were and are still internationally under development (Entrop et al., 2010). However, the use of energy consumption statistics along with degree days in

the form of performance lines, and outside air temperature in the form of energy signature make it possible to evaluate the performance of a building.

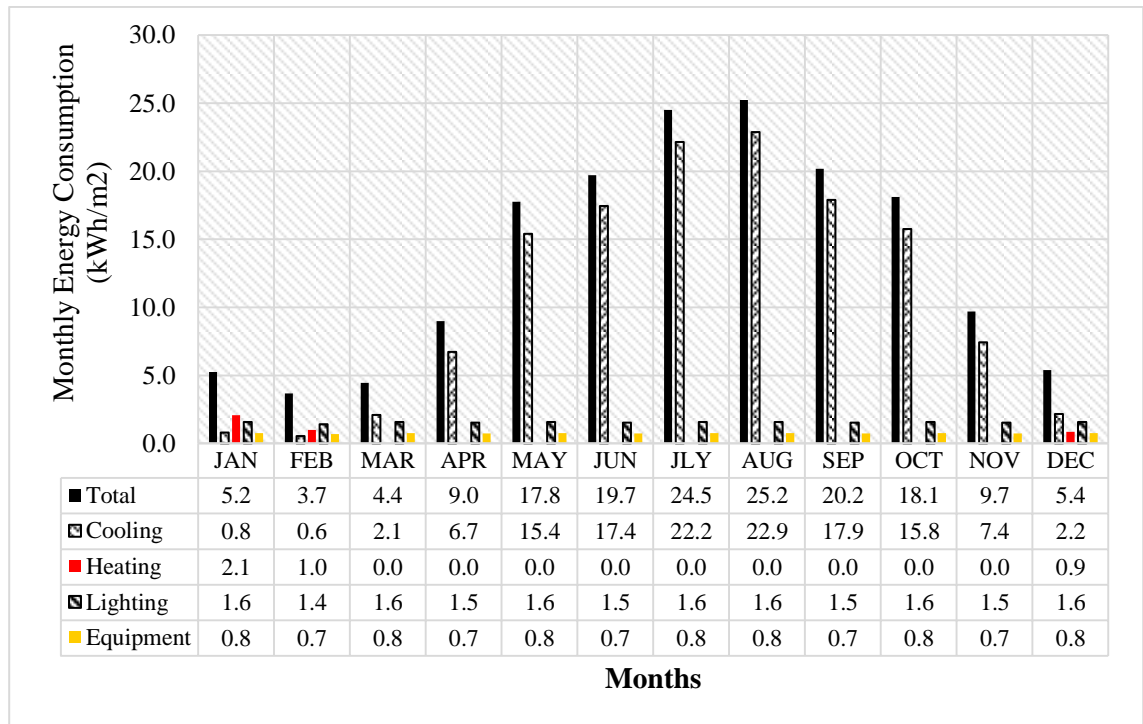


Figure 5.1: Monthly Energy Consumption of Base Case (Total & Segregated)

Performance lines plot monthly energy use against monthly degree day totals (Krese et al., 2012). The points plotted help generate a line and aid in understanding the performance of the building in terms of the slope of the line and closeness of the points to the line. The procedure is therefore applied to assess the energy performance of the base case. **Figure 5.2** shows a plot between monthly energy use and cooling degree days for Dhahran for the year 2012.

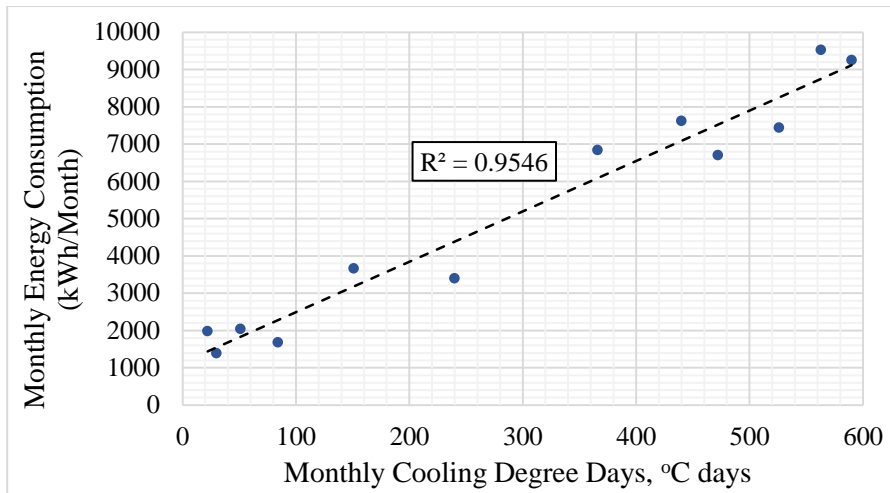


Figure 5.2: Performance Line of Base Case

The dotted line in the above figure represents best fit to performance points. It is the slope of the line that describes the heat gained into the zones through the building envelope. The steeper the slope, more the energy consumption. The slope can be calculated by placing two reference points on the line. Another important consideration in performance lines plot is the scatter of points around or on the line describing the goodness of the fit. This gives an understanding of how well the building performs. More closely the points are to the line, better the correlation and building performance. The goodness of the fit is represented by an R value shown in **Figure 5.2**. The fit for the base case is calculated to be 0.977, however, some points are found to be scattered away from the line.

A building's thermal environment is equally important as its energy performance. Having discussed the energy performance, thermal comfort, therefore, cannot be neglected. Predictive Mean Vote (PMV) is a methodology that helps predict the quality of thermal environment by considering the variable environmental and personal factors and determining the percentage of people dissatisfied (PPD) with the environment. But determining PPD should not be of much benefit for a residential dwelling as the

occupancy is too low when compared to a high-rise building. Besides, the number of discomfort hours can be of great help. The PMV evaluates thermal sensation of people on thermal comfort scale ranging from -1 as slightly cold to +1 as slightly warm. PMV plot of the base case model of the house is shown in **Figure 5.3**. From the plot it can clearly be observed that the house occupants of the base case experience thermal discomfort for majority of days throughout the year. This is as a result of the plot ranging outside the thermal sensation index as depicted in red. A range of -1 to +1 is desirable and thermal comfort is only achieved during some specific weeks in summer followed by spring.

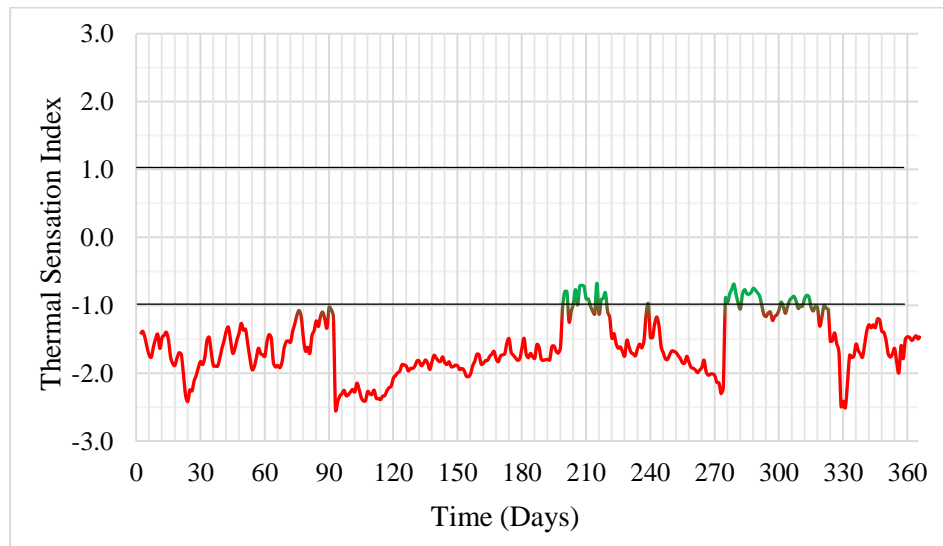


Figure 5.3: Thermal Comfort Assessment of Base Case using Predictive Mean Vote

5.2 Compendium of Strategies


Previous section has seen the energy consumption of the base case for the simulation year for the climate of Dhahran. The fact that the base case represents a single family dwelling clearly signifies it to be envelope dominated. The energy consumed by the cooling system to maintain desired environmental conditions is therefore high and holds great potential to conserve energy. The heat gained into the zones through the building envelope can be

reduced with proper selection of strategies. From the view point of the gist of this thesis, the strategies comprise of a combination of *passive techniques, code and standard*, and *renewable energy* technology as described in chapter 4. Each one is unique in a way that it has been applied to a house in hot-humid climate. Green roof is an entirely different approach accounting for better roof performance as a result of thermal mass and evapotranspiration. Double skin façade used in cold climates for passive solar gains is modified and applied in the base case house model as an active dynamic air envelope. Pitched roofing system is a way to cut down heat gains. This otherwise is not possible with conventional flat roofs. Insulating the building envelope in the best possible way is another such method to tactfully eliminate thermal bridging through the building's structural elements. Exterior shading devices are a means to obstruct direct solar incidence into the zone by carefully designing peripheral overhangs. Building codes and standards help exploit valuable resources in a positive way thereby reducing adverse impact and enhancing environmental benefits. Finally, renewable technologies utilize clean energy occurring in nature and reduce adverse environmental impact and climate change. This section, therefore, presents the influence of all strategies on energy performance of the house. **Table 5.1** shows the energy consumption reduction as a result of each energy conservation measure as well as a compendium of all strategies.

From the table, it can be understood that each strategy played its part in reducing the energy use intensity to its greatest potential. Green roof and double skin curtain wall being new to the climatic zone conserved 5.1% and 6.1% of energy respectively. The unavailability of pitched roofing systems in dwellings in Dhahran showed potential to

decreasing heat transfer and correspondingly cooling energy. For the house model under investigation, pitched roof saved 1.2% energy use.

Table 5.1: Annual Energy Consumption Reduction

			Energy Consumption (kWh/m ² /annum)	Energy Consumption Reduction (%)
Base Case			162.9	-
Energy Conservation Measures	Passive Strategies	Green Roof	154.6	5.1%
		Double Skin Curtain Wall	152.9	6.1%
		Pitched Roof	161.0	1.1%
		Insulating for Thermal Break	150.1	7.8%
		Exterior Shading	163.1	- 0.1%
	Code / Standard	ASHRAE Std. 62.2	113.0	30.6%
		IECC 2012	157.5	3.3%
	Renewable Energy	Solar PV	Energy Production = 40.2	24.7%
	Compendium of Strategies		87.9 - 40.2 = 47.7	70.7%

As pointed out earlier, allowing thermal break throughout the envelope does have less yet acceptable impact on building energy use. Though each strategy had its impact on energy use individually, a set of strategies proved worthy based on the concepts of ZEB by demonstrating higher energy use reductions and producing clean energy. Annual simulation results of each set of strategies can be seen in **Figure 5.4**. Energy consumption reduction of 17.2% was achieved by only implementing passive strategies in the model. Importance of codes and standards can best be understood at this stage. Though two of the four house envelope systems had already complied with IECC 2012 R- and U- value requirements respectively, the rest didn't make much of an effect on house energy use; but the implementation of ASHRAE standard 62.2 clearly conveyed great energy savings.

The two strategies together reduced the energy consumption by approximately 31.1%. PV assumed to be used over pitched roof succeeded in harnessing solar energy, helped meet the equipment and lighting energy demands, and partially compensated grid involvement by meeting approximately 25% of the reduced energy demand of the house.

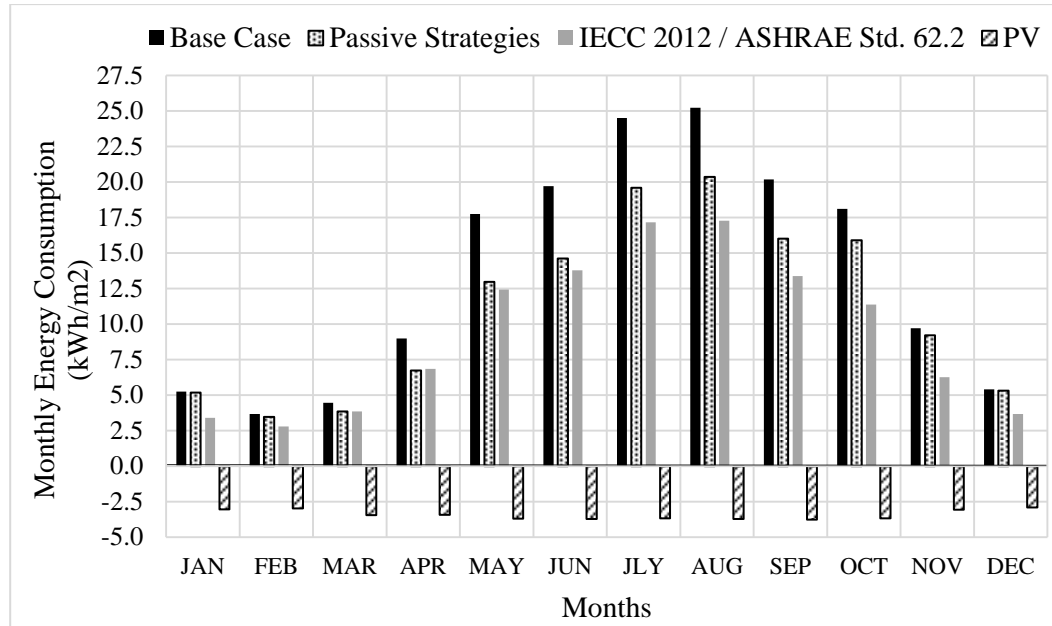


Figure 5.4: Annual Simulation of each set of Strategies

Exterior shading strategy in the form of exterior overhang was employed in the thesis as an energy conservation measure. The strategy, when investigated individually, didn't yield convincing results but showed negligible amounts of savings when used with all other strategies. This indicates that a compendium of strategies has a different impact and helps improve the energy performance. The fact that the house already equipped with tinted double glazing and the WWR being 10% didn't quite allow the required and needed amounts of energy consumption reduction. The exterior shading is now-a-days a standard practice that is still lacking in buildings in Saudi Arabia and must not be neglected even if not able to yield fruitful results.

5.3 Performance Evaluation of nZEB Model

Chapter 5 so far has introduced the performance of base case in section 5.1 with the use of performance lines and PMV analysis. A comprehensive discussion on the impact of strategies utilized for the set objective were discussed in section 5.2. This section, therefore, presents the influence of all strategies on energy performance of the house, and evaluates the performance of the new design in terms of the characteristic concept of near-Zero Energy Building (nZEB). **Figure 5.5** shows the reduced monthly energy index as a result of all strategies in contrast to the base case monthly energy index. It is clear that the nZEB model has greatly reduced the energy demands thereby reducing grid involvement for the remainder of the energy. The annual energy use index calculated to be 47.7 kWh/m² with a total percentile reduction of 70.7%. It can as well be noted that winter months, i.e. January, February and December, have very low energy use. As cooling is at its minimum during these months, it is lighting, equipment, and heating, that have contributed to the energy consumption the most.

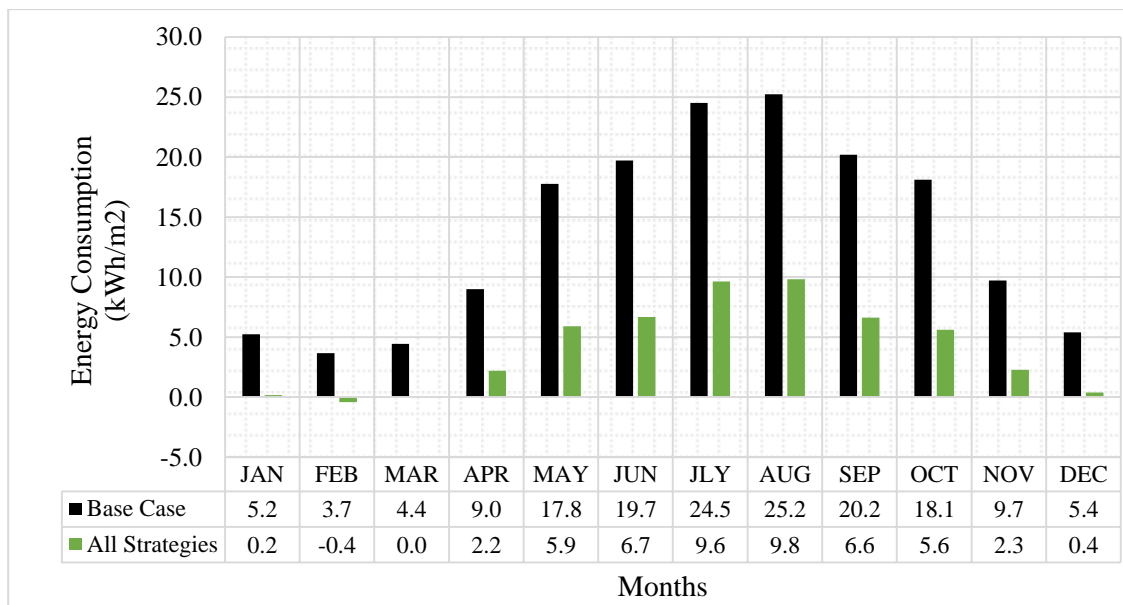


Figure 5.5: Monthly Energy Use Index of nZEB Model

PV system being able to meet the lighting and equipment load has helped provide the house with 28.7 kWh/m²/month of electricity and an additional extra electricity production depending on the availability of solar resource. This not only reduced gross monthly energy consumption during winter season but also partially offset the remainder electricity requirement from the grid. Implementation of strategies depicted a great impact on cooling energy use during summer season.

The energy performance of the nZEB model is then studied by employing the same approach as done for the base case model. The procedure of performance lines is therefore again applied to assess the energy performance. **Figure 5.6** shows plots between monthly energy use for both base case and nZEB models, and cooling degree days for Dhahran for the year 2012. The plotted lines represent best fit to performance points.

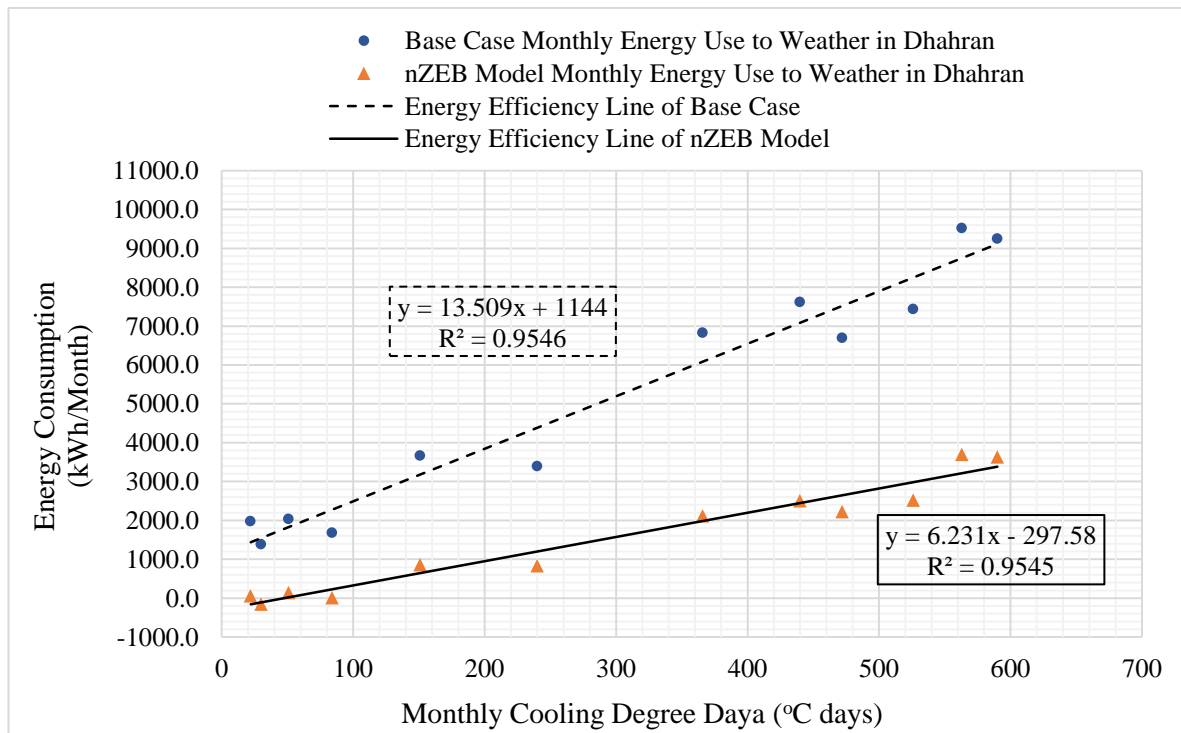


Figure 5.6: Performance Line of nZEB model

It is evident from the plots that the slope of the performance line of nZEB model is less than the slope of base case line. This unmistakably signifies that heat gained into the zones and energy consumed by nZEB model for the required number of cooling degree days is less than the base case model. Scatter of data points on the other hand strengthens the discussion even more. The points of nZEB model seem much closely packed to the line and depict an improved fit over the base case. Thus, the correlation of data points with the performance line for nZEB model is better than its counterpart demonstrating better energy performance. Owing to the distribution losses, the performance line of nZEB model, at the moment, is unable to explain the non-weather dependent energy consumption. This, being one of the major limitations of this thesis, is because the PV is not integrated with the roof structure and the energy produced is assumed to be provided to the house separately. The monthly energy index met by PV is therefore simply subtracted from monthly energy index of the house to represent actual energy performance based on the limitation as mentioned above. Had it been integrated, the performance line would have been approximately horizontal with a lesser slope value, data points more closely packed indicating even much better fit, and the line ultimately demonstrating the non-weather dependent energy consumption of the house.

The results obtained and the study of energy performance have developed great interest in assessing thermal comfort of nZEB house model. PMV analysis suggests plot between time and thermal sensation index be within the limits of -1 and +1 as mentioned in section 5.1. The nZEB model, as shown in **Figure 5.7**, has depicted great improvement over base case model in this regard. With the implementation of different strategies the plot as represented by the continuous line has shown an upward shift on thermal sensation scale.

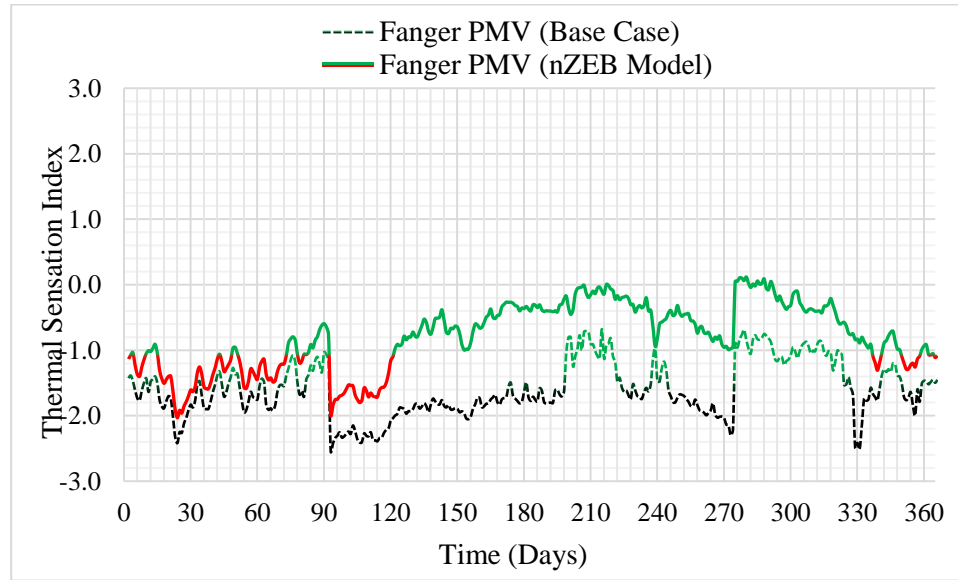


Figure 5.7: Thermal Comfort Assessment of nZEB Model using Predictive Mean Vote

Thermal comfort which only was achieved during few weeks in summer and fall seasons for the base case now seems more predominant from April onwards in the nZEB model. The main reason for such a shift lies in the implementation of all strategies into the base case model. Influence of one strategy on thermal comfort did not show much of a variation except green roof, pitched roof and ground thermal insulation. Green roof besides reducing heat gain into the space provided thermal mass in the form of growing media over the roof structure which eventually aided in enhancing the quality of indoor thermal environment. Adding a layer of thermal insulation preserved heat into the house but slightly increased the energy consumption.

5.4 Cost-Economic Aspects of PV System

The design of PV system using HOMER in chapter 4 has seen an optimised system architecture in terms of 8.7 kW PV with 56 Trojan L16P batteries and a 4.1 kW inverter. The techno-economic analysis was as well performed by HOMER considering the cost for

one unit of power or component and corresponding operation and maintenance costs as applicable. The cost of the system representing the initial, replacement, and operation and maintenance expenses is shown in **Table 5.2**.

Table 5.2: Life Cycle Cost of PV System

Component	Capital (\$)	Replacement (\$)	O&M	Salvage	Total
PV	43,500	0	0	0	43,500
Battery	16,800	28,000	14,000	-1,202	57,598
Inverter	3,690	2,460	0	-820	5,330
System	63,990	30,460	14,000	-2,022	106,428

A techno-economical assessment of PV in a residence in Jordan was presented in a study (Al-Salaymeh et al., 2010). Payback period was calculated based on various economic factors. Results for payback period of the system based on escalation of inflation rates every year were presented. The costs associated with PV system features and components were assumed to remain constant over the years throughout the life cycle of the system. It was suggested that an annual increase of 2% and 3% in electricity rates would yield the capital invested in 29 years and 25 years respectively. Another study pointed out the infeasibility of solar PV application in Saudi Arabia due to low electricity rates (Taleb and Sharples, 2011). Governmental subsidies for offsetting fossil-fuel electricity, capital cost subsidy for renewables, and financial incentives such as feed-in tariffs and net metering were proposed to boost the viability of the technology.

The costs associated with the PV system design for the 4-bedroom house using HOMER seemed to be following similar trail for the assessment of payback period. **Table 5.3** presents the considerations for calculation of payback period for the designed system.

Table 5.3: Considerations for PV System Payback

Parameter	Magnitude
Annual energy consumption of nZEB model w/o PV	33,977.7 kWh
Annual production (adjusted based on real life conditions by HOMER)	15,392 kWh
Annual energy consumption of nZEB model w/ PV	$33,977.7 - 15,392$ = 18,585.7 kWh
Saudi Arabian electric energy rate	SR 0.26 / kWh = \$ 0.069 / kWh
Annual electricity bill	$18,585.7 \times 0.069$ = \$ 1282.4
Annual inflation	0%, 2%, 4%, 6%
Government subsidies and credits	50% of total system cost

Considerations to calculate the payback period are reflected in the above table. Offsetting fossil-fuel electricity, renewable energy cost credits, and other financial incentives have all been assumed in the form of government subsidies. Therefore, payback period for different considerations based on total system cost is depicted in **Figure 5.8**. The calculation clearly signifies that solar PV can only be feasible in Saudi Arabia if the government takes active part in promoting renewable energy. The use of PV and annual escalation of electricity rates may help find answers to the questions concerning PV system payback. Proposed considerations include inflation of 4% and 6%, and 50% of total system cost in the form of government subsidies. The plot in **Figure 5.8** indicates a decline in number of years upon considering increasing inflation rates. The proposed cases meet the payback of \$53,214 in less than the assumed life cycle of the system.

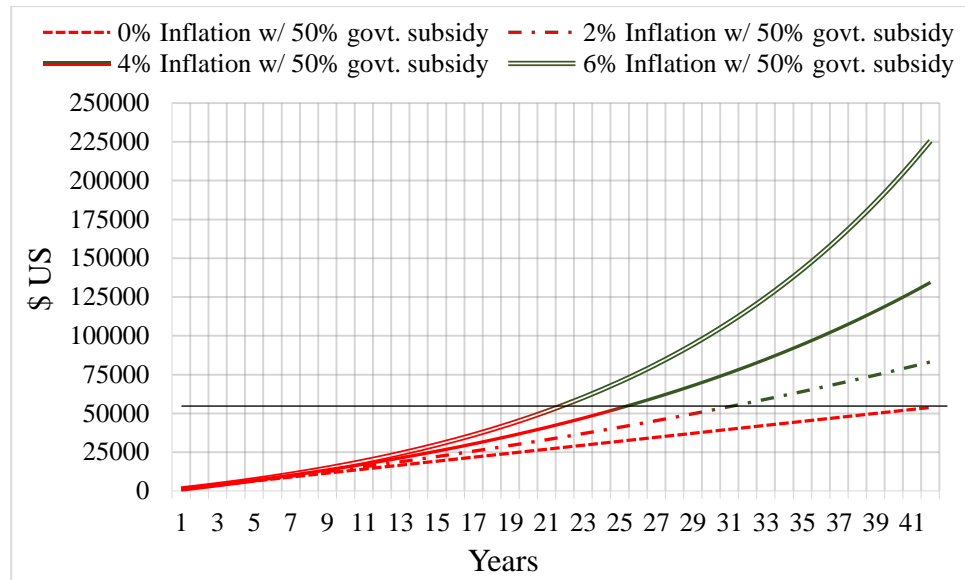


Figure 5.8: Payback Estimate based on Proposed Considerations

The costs shown in **Table 5.2** do include end of life replacement costs associated with system components, and operation and maintenance costs. This analysis therefore include life cycle cost based on net present value of the system. The transportation, installation, balance of system, and labour costs of PV have however been considered in the capital cost as \$5000 per unit kW of power.

CHAPTER 6

Conclusions, Recommendations and Prospects

6.1 Conclusions

6.1.1 Achieving near-Zero Energy Performance

The research initiative taken up in this thesis is first of its kind for a hot-humid climate as characterised by the weather in Dhahran. It was carried out to evaluate the near-zero energy performance of an existing 4-bedroom single family dwelling at King Fahd University of Petroleum & Minerals with the help of state-of-the-art energy simulation program DesignBuilder. The idea behind the innovative concept of ZEB resulted in investigating most proper passive design strategies, utilization of relevant code and standard, and solar PV technology working in tandem to achieve nZEH design in Saudi Arabia. Though the objective set to accomplish the task was just one, it seemed exhaustive for a Master of Science thesis in terms of a study first of its kind in Saudi Arabia. The research carried out was divided into three phases. The first phase provided insights on studies related to ZEB design highlighting relevant concepts and requirements. This included the investigation of proper passive strategies and their impact on energy consumption, effect of relevant code and standard, use of PV technology to offset a specific amount of load from electricity grid, and review of BPS programs and selection based on modelling capabilities in the light of ZEB design concepts. As the research focussed on enhancing the performance of an existing house, the second phase emphasised on base model development, and verification based on real-time performance

monitoring. The third phase looked into the implementation of each strategy investigated for energy performance. The strategies investigated were green roof, double skin curtain wall, exterior shading, pitched roof, insulating for thermal break, International Energy Conservation Code 2012, ASHRAE standard 62.2, and solar PV. Energy performance indicator kWh/m²/annum was utilized to assess the impact of each strategy. Thermal comfort analysis was as well performed. Personal and environmental factors of thermal comfort were given consideration in thermal comfort analysis by using Fanger's predictive mean vote model on thermal sensation scale throughout the year.

Simulation results of the base case model of the house conveyed a total energy consumption of 162.9 kWh/m²/annum depicting segregated energy end-use of 80.6% for cooling, 2.4% for heating, 11.5% for lighting (inclusive of exterior lighting) and 5.5% for equipment. Majority of energy saving potential was found in cooling, and thus various strategies were investigated accordingly. Thermal comfort analysis of the base case didn't quite show the PMV curve within comfort limits except for few weeks in summer and late fall seasons. The simulation results of the house model depicting ZEB concepts conveyed a total energy consumption of 47.7 kWh/m²/annum. Majority of energy consumption reduction was found on the cooling side. The PMV curve showed a significant shift towards thermal comfort index on the thermal sensation scale. The research conducted seems appealing at one instance but simultaneously suffers from non-integration of solar PV at other instance. The pitched roof of the house is sloped at an optimum angle of 23.7°. It is assumed that PV panels are arranged over the pitched roof to meet equipment and lighting load and to provide surplus electricity to reduce grid penetration in meeting the house loads. When the application of solar PV is discussed / implemented, it is

inevitable to look into other benefit it provides in the form of domestic hot water (DHW) in hot climates with appropriate arrangement of solar thermal systems. Though this aspect has not been given specific consideration in the thesis, a brief discussion on it may suffice its prospects for application. Surface temperatures of PV modules reach as high as 80°C in summer. Efficiency of PV is a function of module temperature and decreases with every 1°C rise in temperature. Maximum output is achieved at standard test conditions of 1000 W/m² solar irradiance and 25°C module temperature. Real life situations demand decreased solar irradiance and increased or decreased air temperature depending on the climate. The difference between air and module temperatures in summer in hot climates drastically decreases the efficiency of PV leading to a reduced output. Thus, it is assumed that appropriate solar thermal arrangements are made for PV to meet the desired electrical load of the house year round. Solar thermal is then presumed to meet DHW demands of the house.

6.1.2 Toward Zero Energy Performance

Around 70% reduction in total energy consumption has been observed by only implementing the strategies discussed in this study. Various other strategies such as solar cooling technologies, energy efficient lighting systems, equipment and HVAC system, and control systems were however not given consideration. The nZEB house model in light of unexplored strategies still seems to hold great potential to reduce energy consumption, and represents the possibility of a reference model for ZEB in hot-humid climates. Sustainability defines the exploitation of resources in a positive way by demonstrating usefulness to the user and the environment. Energy comes in many forms and has now become a basic necessity of life. Thus, the nexus between water and energy

should never be undervalued. With the scarcity of fresh water and the energy being spent to make water available is a challenge. The house, therefore, should not only be energy efficient but also water efficient. Green roof requires water for irrigation and has an impact on water usage and related pumping energy consumption. Application of efficient water systems as per relevant sustainability assessment criteria must be taken care for energy conservation. Another important measure is to reduce distribution losses and heat gain from / to supply air in the distribution system. Efficient distribution system is a compliment to the energy it consumes and to the comfort conditions to be met in the zone. Besides all, occupant education about the technologies used in the house does have a great influence. Careful and responsible actions of occupants help keep energy usage trends to a minimum.

6.2 Recommendations

A case study based research was undertaken in this thesis. A single family 4-bedroom faculty housing depicting most common design and construction methods in the region was considered. The thesis focussed on an existing building and then on implementation of proper strategies for energy conservation. This limited the thesis to the use of some specific strategies for near-zero energy performance. Research was anyhow carried out to achieve the desired performance which affected its execution and time for completion. Following are the recommendations in relation to the research carried out:

1. It is observed that the aspect ratio of the house is close to 1:1.5. The house is more like a villa than a single family residence. An aspect ratio of 1:1 is recommended for reduced heat gains through the envelope. This ultimately reduces the cooling energy consumption.

2. Reducing the aspect ratio does reduce the footprint. Desired floor area can be maintained by designing the house from the ground-up in terms of number of floors. An extra floor could therefore be included in the design to meet the needs of the family. Designing a compact house even reduces the need for thermal insulation.
3. A unitary single zone system provides cooling to the house. Unitary multi-zone system with set-back temperature control is recommended. Each single zone (partition) on a floor can then be controlled for better energy performance and thermal comfort.
4. The solar PV system assumed to be housed on the roof must incorporate appropriate arrangements to take away the heat from the modules for efficient and year round performance.
5. Drip irrigation system is recommended for green roof irrigation to reduce wastage of water. Appropriate strategies to recycle non-potable water for green roof irrigation must be implemented.
6. Exterior shading devices such as overhangs and fins must never be neglected and are recommended as a standard practice in hot climates. Placement of large windows on east and west orientations as observed in the house is not recommended.
7. Thermal bridging through the building structure along the envelope must be reduced by incorporating thermal insulation toward the exterior of thermal mass.
8. Government involvement and encouragement for the use of solar PV can help implement the technology. Hence, it is recommended home owners seek financial support from regional governing organisations.

9. Not much difference in energy consumption was observed by orienting the house exactly along east-west axis for the current envelope configuration. Therefore, it is recommended that house be oriented exactly along east-west axis for maximum electricity production from solar PV.

6.3 Future Work

The thesis mainly focussed on investigating proper strategies and integration of solar PV technology to achieve nZEB home design in Saudi Arabia. Integration of two physical / thermodynamic systems or technologies takes into account the heat exchange between them. This seems to be absent in this simulation based research depending on the capability, selection and availability of state-of-the-art software tool(s). Though proper integration as mentioned above wasn't possible, the study at least assumed integration in the form of solar PV being placed over pitched roof on the house fabric and within the house footprint. Besides the issue of proper integration of technologies, thesis was limited to quite noteworthy aspects. All these represent lessons learned over the period of execution of this thesis, and future work must be extended based on these limitations. Following points briefly describe the future of research in the area of Zero Energy Buildings for hot-humid climates:

1. Exploring new innovative home designs in terms of building shape, orientation, and envelope criterion WWR. The design should be developed from the scratch as a concept instead of simply modifying the design of an already existing house.
2. Passive design strategies which have not been given consideration in this thesis must be assessed for their feasibility in terms of application to climate, regional construction methods, availability of skilled labour, and economics. Some of these

as a potential interest to hot climates include solar chimney, phase change materials (PCM) and thermal massing.

3. The research must look into proper integration of solar systems with building envelope (BIPV/T). Careful considerations must be given to PV system design. Other renewable energy options must as well be explored.
4. Natural ventilation and mechanically controlled night ventilation systems for cooling demand reduction can be taken up in future research.
5. Each floor of the house represented one single zone for simplicity. Multi-zonal influence on energy consumption in relation to spatial arrangements depending on type of activity and solar gains can be studied.
6. Many other strategies as mentioned in section 6.1.2 can be addressed.
7. As cooling system is the key player in energy use and thermal comfort, future studies must further see an in-depth investigation of thermal comfort criteria in terms of each strategy being applied to the design.
8. Economic considerations regarding initial and maintenance costs, and payback period estimates for ZEB must also be carried out.

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