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

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INTRODUCTION

Recent development has seen a drastic increase in energy use trends in Saudi Arabian buildings leading to a demand for an effective course of action for energy conservation and production. A case study-based research initiative exploring near-zero energy potential in Saudi Arabia was undertaken. A 4-bedroom detached single-family faculty residence at King Fahd University of Petroleum and Minerals (KFUPM) representing common regional housing design trends was utilized. A base case simulation model of the house was developed and validated using short-term and real-time energy consumption data. Three sets of strategies: *passive design strategies, representative codes and standards*, and *renewable technology* were employed in the new design of the house. Passive strategies comprised a *green roof*, a *ventilated wall system*, a *sloped roof*, and *insulation for thermal bridges*. These alternatives helped reduce the annual energy consumption of the house by 17.2%. The most recent version of the International Energy Conservation Code (IECC 2012) was also incorporated along with ASHRAE Standard 62.2 for ventilation. The code and standard together reduced the annual energy consumption by 31.1%. Solar PV was then utilized to reduce grid utilization for the remainder of the house energy loads. This strategy provided 24.7% of the total energy consumed annually. A combination of strategies showed a 70.7% energy consumption reduction, thereby decreasing the energy index of the house from 162.9 to 47.7 kWh/m^2/yr. The Zero Energy Building (ZEB) concepts and strategies utilized in this study demonstrate a socially responsible approach to achieving near-zero energy performance for an existing house.

KEYWORDS:

solar energy, near-Zero Energy Building (nZEB), near-Zero Energy Home (nZEH), passive strategies, Solar Photovoltaic (PV)

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1. SUSTAINABLE APPROACHES TO DESIGNING AND CONSTRUCTING RESIDENTIAL BUILDINGS

Sustainability creates and maintains the conditions under which humans and nature can exist in productive harmony and facilitates fulfilling the social, economic and other requirements of present and future generations [1]. In the built environment, sustainability refers to building using solutions that are environmentally responsible and resource-efficient throughout its life-cycle. In recent decades, the building industry has adopted a more environmentally friendly approach, with a view toward minimizing the energy, carbon, and environmental footprint of different types of buildings. This change had been driven by a genuine need to optimize and conserve natural resources and to minimize the operating costs and environmental impacts of buildings while increasing their functionality, efficacy and comfort for occupants. The statistics of the Saudi Electricity Company (SEC) for 2010 [2] conveys that the building industry in Saudi Arabia accounts for approximately 76% of overall consumption out of which the residential sector accounts for about 51%. Similar observations can be observed for 2011 [3]. Further, the residential sector marked a 10% increase in 2012 [4] in comparison to 2011. Saudi Arabia has experienced a gradual increase in energy demand over time in the residential sector. This can be attributed to new construction each year, which increases the electric load on the grid. These energy demands mostly depend on conventional energy sources that are non-renewable. 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. A sustainable approach to new construction would reduce dependence on the grid. Hence, meeting these demands in a sustainable and socially responsible way is among the best approaches to utilize any of the available renewable energy sources or combinations thereof. One such approach is the application of the concept of near-Zero Energy Homes (nZEH) that utilizes both passive design strategies and PV technology in home design.

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 and using renewable technologies to supply these needs. It produces as much energy at the site as it uses yearly [5]. It is a building using 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 the International Energy Agency [6], a ZEB is a traditional building housed with large photo collectors and photovoltage systems. Iqbal [7] described a ZEH as: "*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*." In defining a zero energy solar home, emphasis is put on the use of solar thermal and solar PV technologies in meeting the energy requirements of the home's yearly load [8]. A clear and common definition was lacking to understand the term "zero energy," which finally led to four different conceptual definitions of zero energy, *i.e. what measurable quantity should be zero* [5]. These included *net-zero site energy, net-zero source energy, net-zero energy costs and net-zero energy emissions*. Marszal, et al. [9] provided a review of ZEB definitions in the light of issues such as metric of balance, balancing period, type of energy use and energy balance, acceptable renewable energy supply options, energy efficiency targets, etc. that depend on grid connectivity. Pless and Torcellini [10] presented a classification system for Net Zero Energy Buildings (NZEB) depending on the type of renewable used. The classification ranges from "ZEB A" through "ZEB D" with ZEB A ranked as the best, ZEB B and ZEB C ranked as better and ZEB D ranked as a good energy supply option for the building. As ZEB needs to produce energy for its requirements, 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 low such that the renewable is capable of supplying it. This could be achieved by improving the energy efficiency of the building. Pacheco, et al. [11] through their building design criteria conveyed the importance of reduced energy demand for heating and cooling in residential buildings. An overview of solar energy potential and thermal energy storage were key components of reduced energy consumption [12]. Loonen et al. [13] presented a comprehensive review of climate adaptive building shells (CABS), and highlighted the importance of climate adaptive design of buildings for sustainability in the built environment. The first prerequisite of a ZEB is designing a house that responds to its site and climate [14]. This concept is known as passive design. Passive design utilizes solar energy to heat or cool the building or a part of the building and reduces the 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 [15]. However, dependency on active systems can only be reduced in hot climates. Passive design strategies include *orientation, high R-value wall assemblies, high R-value roof assemblies, window-wall ratio (WWR), low-e glazing, building massing, shading, etc*. The NZEB design concept is a progression from passive design [16]. Therefore, the next step would be to take advantage of 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, which helps achieve movement towards the zero energy mark. Although ZEB is not easy to achieve, a step forward could be taken by investigating the viability of the 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 viewpoint of a single-family dwelling, it is called a “near-Zero Energy Home” (nZEH).

2. DESIGN STRATEGIES AND STUDIES

Various studies have investigated the viability of ZEB design solutions. Hutton [17] presented a study on Net Zero Energy Schools that explained the viability of the most typical design strategies to achieve net zero energy status. The main area of focus was the Net Zero Pyramid that incorporated the most typical design strategies to achieve a 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*. Another strategy used to design net-zero compliant buildings is explained in a two-step net-zero process [18]. 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 is based on relevant building codes where pre-defined high performance measures are selected under various categories. The performance path is based on the use of appropriate Building Performance Simulation (BPS) tools for design process evaluation. 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. Wang et al. [19] in a study carried out in the United Kingdom on zero energy house design discussed and compared 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 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. EnergyPlus was used for façade design, 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, optimal design solutions were provided. 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*. Another study carried out an exhaustive technical review of building envelope components [20]. The idea was to significantly reduce the energy consumption with the help of energy efficient strategies. To start the task, the authors considered a variety of energy efficient walls. These included "Trombe" walls, glazed walls and ventilated walls. Also considered were different fenestration technologies with aerogel, vacuum glazing and frames. In their classification of building envelope components, advancements in green roofs, PV roofs, thermal insulation, thermal mass, phase change materials, air tightness and infiltration were given consideration. Incorporating all of the aforementioned approaches into the building provided a holistic energy efficient building design that reduced energy consumption and cut down respective costs. This was the passive design approach, and the elements mentioned were passive strategies that could be utilized depending on certain climatic considerations. A research initiative on building energy models demonstrated a net-zero energy residence by combining passive and active strategies in six different climates and in three simple steps [21]. These included *(1) passive low-energy design strategies and energy efficiency measures, (2) selection of a combination of strategies, and (3) 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 indicated an estimated reduction in annual energy consumption of 19-30% compared to a baseline code-compliant home. A study carried out in Sweden focused on the investigation of energy performance of newly built, low-energy buildings [22]. The performance of passive homes to meet European goals by employing Building Energy Simulation (BES) was investigated. 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 [23]. This led to reductions in daily fluctuations of indoor air temperatures which resulted in maintaining the desired comfort level for longer periods of time. Zhang [24] investigated various green-technologies to achieve the desired targets of energy efficiency and sustainability in buildings. In addition to these, a study provided an insight on the function of form factor/building shape on energy [25]. Two aspects related to building shape and energy consumption were highlighted. Review of passive solar design strategies suggested that high levels of energy performance could be achieved when an optimal combination of several strategies was applied [26]. A comparative analysis of exterior walls coupled with thermal mass walls was undertaken [27]. The walls were arranged such that the outer wall was a traditionally insulated one followed by thick thermal mass wall towards the interior. An all year round energy performance and thermal comfort study was carried out on the behaviour of solar walls in a residential building in Mediterranean climatic conditions [28]. The study aimed to investigate the influence of a "Trombe" wall's thermal behaviour and its influence on heating and cooling energy needs. A completely new idea of an Active Dynamic Air Envelope (ADAE) facilitated energy performance improvements and thermal comfort enhancement of buildings in bidirectional climates [29]. 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 [30], presented an overview of a passive strategy for natural ventilation using a solar chimney that traps heat from the sun and enhances the buoyancy effect for passive ventilation. A roof covered with vegetation is known as a green roof and has become recognised as a valuable passive strategy to reduce roof heat transfer and improve thermal comfort. Green roofs are of three types: namely modular, extensive and intensive. The modular systems are comprised of trays of vegetation spread all over the roof. 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, on the other hand, is a heavy weight construction depicting a garden-like environment over the roof with depths of growing media greater than that of modular or extensive roof types. Interest was shown in the energy balance using a Green Roof Integrated with PV systems (GRIPV) [31]. The strategy reduced solar heat gains from the roof of the building and thereby reducing the cooling energy. The use of a PV system offset the reduced demand of the building. Cost savings by green roofs in arid climates were presented [32]. The effectiveness of a green roof on energy consumption of a residential building was studied in Cairo. Parametric analyses included the following: *thickness of green roof soil, conductivity of green roof* and *building aspect ratio*. It was found that cost savings of the green roof ranged from 15-32% compared to a traditional roof. Research on various strategies to mitigate the effects of city and urban heat islands was considered [33]. The study provided a review of green roof strategies to lessen heat islands. Another study looked into the impact of a green roof on building energy performance for a single family house in a temperate French climate [34]. A unique research endeavour was undertaken at the University of California on the effect of installing solar PV panels on roof heat transfer [35]. The roof of the building was partially covered with PV panels and measurements of thermal conditions throughout the roof profile were conducted. Thermal imagery displayed ceiling temperatures at exposed roof portions 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/m^2 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. The effects of shading of Building Integrated PV (BIPV) on roof surface temperature and heat transfer on a university building were examined and quantified [36]. 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 [37]. Direct and indirect benefits of installing PV systems on existing residential homes in northern climates were provided in a research study [38]. Renewable energy options and viability of solar PV in the residential sector in Saudi Arabia were explored [39]. 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) [40]. Lopez and Frontini [41] addressed the importance of integrating the building, existing or new, with solar energy systems.

The published literature on ZEB, nZEB, ZEH for hot and hot-humid climates as observed in Saudi Arabia is rare. Passive House standard governs the design of ZEBs in colder climatic conditions as observed in the UK and USA. Passive House Planning Package (PHPP) is a tool that aids in the design of a passive house/highly energy efficient house in the UK and other colder climatic conditions. Those do not directly apply to the hot and hot-humid climate of Saudi Arabia. Therefore, design strategies can be adopted and implemented in the design of highly energy efficient house/buildings in hot/hot-humid climates.

3. THE STUDY APPROACH

The house energy performance under various strategies is assessed through an energy simulation model that is developed on the basis of collected data pertaining to the thermo-physical characteristics and energy consumption of an existing detached single family house. The thermo-physical properties of the model were estimated based on related data available in the construction documents of the chosen house. The *DesignBuilder* [42] energy simulation software was used for formulating the base case model representing the thermal and energy behavior of the house. Attia and De Herde [43] discussed the use of Building Performance Simulation (BPS) tools in designing NZEB. Comparisons between ten tools showed that DesignBuilder provided most of the early-phase design features. Besides being able to offer a graphical user interface (GUI) to today's widely used energy simulation engine EnergyPlus, DesignBuilder meets the requirements highlighted in ASHRAE Standard 140-2011 [44], and also holds good for carrying out performance-based analyses to design NZEB at the first step. A detailed energy audit was conducted to collect physical, thermal and operational characteristics, as well as the actual monthly energy consumption data that are necessary for devising an accurate model. The house was physically surveyed and relevant data obtained. The base case model was then attuned to achieve acceptable performance by comparing its prediction with short-term actual energy consumption data collected as part of the audit process. The attuned base case model was then used to assess the impact of several strategies on the energy and thermal performance of the house. Figure 1 illustrates a flowchart showing the components of the suggested approach for applying passive energy conservation measures and solar energy technology for achieving an nZEH model.

4. BASE CASE FORMULATION AND VERIFICATION

4.1 Base Model Development and Formulation

A case study based research initiative exploring near-zero energy potentials in Saudi Arabia was undertaken. A 4-bedroom single-family faculty residence at KFUPM was used to represent the most common regional housing unit (i.e. the Eastern Province, Saudi Arabia) in terms of spatial organization, construction systems, used building materials and workmanship. The house consisted of two floors with a total area of approximately 377 m^2. The area of the ground floor and first floor was around 210 m^2 and 167 m^2 respectively. The house was 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 ground floor, identified as the living area, consisted of an entrance area, a dining room, a study room, a kitchen and a laundry room, and the first floor was the sleeping area consisting of four bedrooms. The floor plans and the cross-section of the house can be seen in Figure 2.

FIGURE 1: Flowchart showing components of the suggested approach for achieving improved energy performance leading to n-ZEH model.

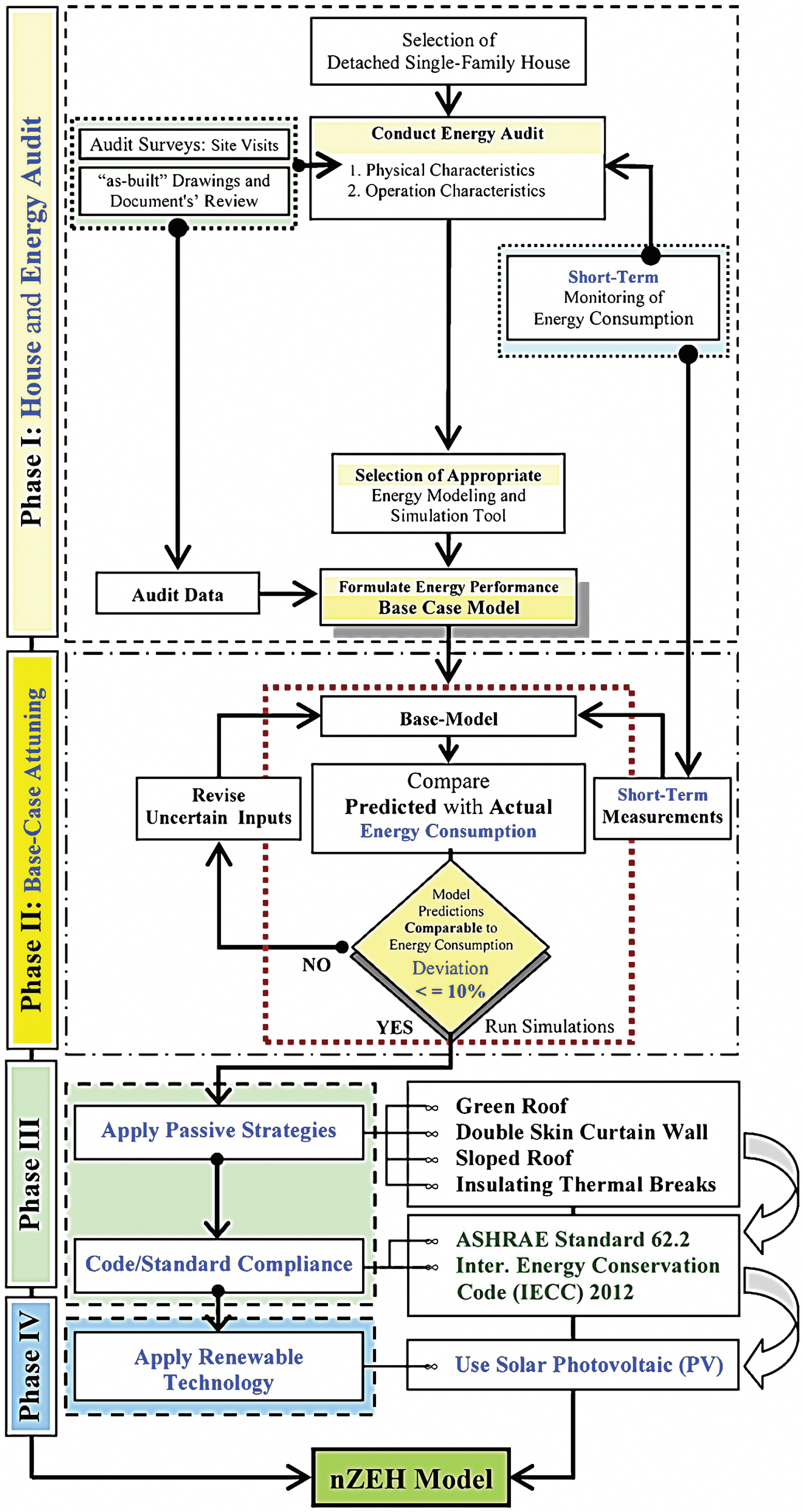


FIGURE 2: The house floor plans; (a) ground floor, (b) first floor and (c) cross-sectional view (Source: Projects Department, KFUPM).

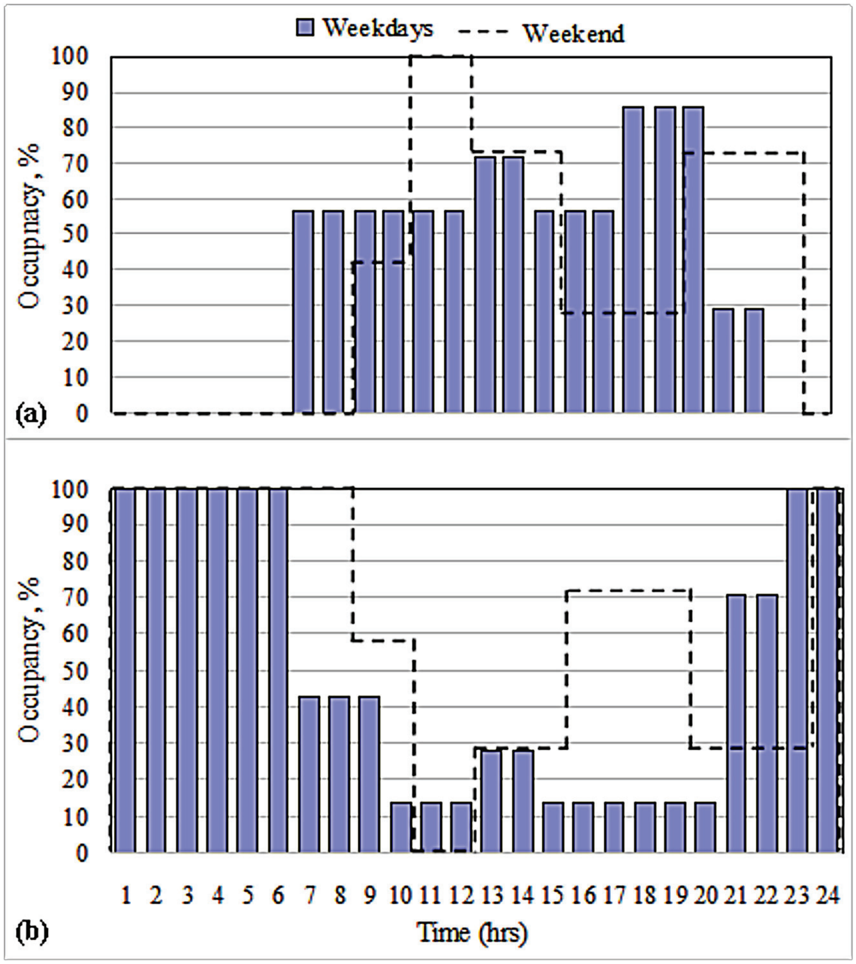
Looking at the figure, one can notice the differences between the floor areas. The first floor occupied less area than the ground floor and the remaining area was open to the outdoors, thereby allowing the possibility of accommodating packaged terminal air-conditioning units. A detailed description of the house is given in Table 1.

TABLE 1: The house characteristics and specifications of the base case model (***See Figure 2)***.

Component	Description / Characteristics
Location	Dhahran, Saudi Arabia (26.27 N latitude, 50.15 E longitude, and 17.0 m above sea level)
Weather	Dhahran Weather Data, 2012
Orientation	Front Entrance 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 in place, dense)
Infiltration	1.0 ACH (Ground Floor); 0.5 ACH (First Floor) {Initial Base Case}
Occupancy	7 People
Lighting Power Density (LPD)	21 W/m^2 (Ground Floor); 13 W/m^2 (First Floor)
HVAC System	Residential System (Constant-Volume DX units) **Ground Floor** Capacity: 142.8 MBtu/hr = 11.9 tons Supply air flow: 4840 cfm = 11.3 ACH *(Approx.)* Outside air flow: 780 cfm = 1.8 ACH *(Approx.)* **First Floor** Capacity: 112.8 MBtu/hr = 9.4 tons Supply air flow: 3760 cfm = 9.4 ACH *(Approx.)* Outside air flow: 245 cfm = 0.6 ACH *(Approx)*

A base case simulation model was developed using a state-of-the-art software tool, i.e., DesignBuilder. DesignBuilder provides a variety of tools to add and draw blocks that eventually take the shape and form of a building. Besides incorporating the design specifications of building envelope systems in the model, emphasis was 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 was assumed to have a different level of airtightness. Separate occupancy schedules were defined for system availability and operation schedule. Figure 3 shows the occupancy schedules for ground and first floors during weekdays and weekends. The equipment definition includes total electrical wattage and amount of heat gain in the zone in terms of load, usage factor and radiant fraction of each piece of equipment. The usage factor of the equipment was assumed based on hours of operation per day. The heat gains as a result of equipment usage (hr/day) and radiant fraction were adapted from ASHRAE fundamentals handbook 2009 [45].

FIGURE 3: Occupancy profiles during weekdays and weekend for (a) ground Floor (b) first Floor.

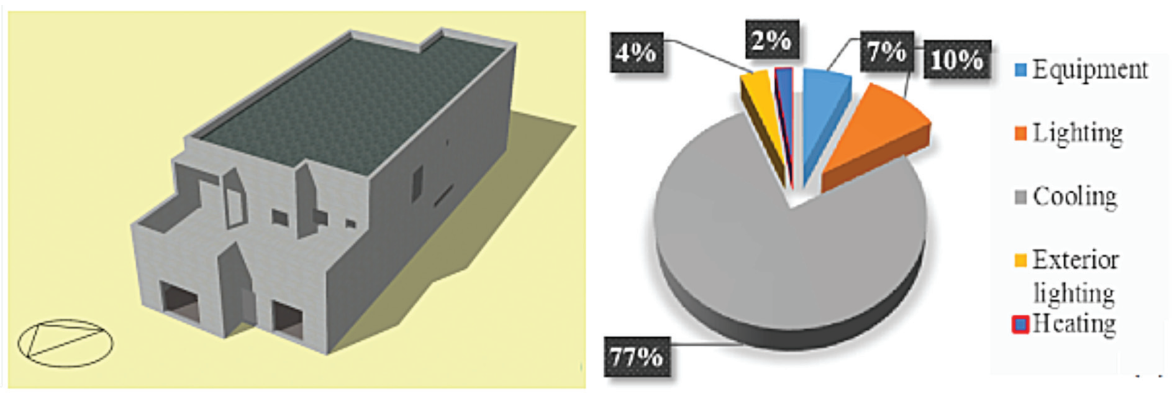


Though there were a number of rooms in the house, each floor was considered as one single zone for simplicity as each floor's HVAC system was controlled by one thermostat set-point. Specific attention to each input parameter helped define the base case simulation model of the house. Figure 4(a) shows the developed model of the house.

4.2 Base Case Attuning and Validation

Further to the definition of building envelope systems, lighting systems, cooling systems, equipment, and other model related input parameters, the base case model was simulated for the location of the house. In summary, the annual energy consumption of the house was found to be 136.1 kWh/m^2. The fuel energy breakdown depicts a percentile share of 6.6% for equipment, 10.0% for general lighting, 77.4% for the cooling system as the major consumer of energy inclusive of fans, 2.3% for heating and 3.7% for exterior lighting as shown in Figure 4(b). The cooling energy of the base case house demonstrated agreement with the cooling energy consumption values of the 4-bedroom single family residential dwellings of KFUPM. The cooling energy consumption share was found to be about 73% of the total energy used [46]. The total energy consumption was approximately 193 kWh/m^{2}yr, which was higher than might have been expected in comparison to the base case results. However, the findings represented the construction of building envelope systems, such as walls and roof, and the efficiency of operation of the cooling system from decade old units from 2000 or earlier. Therefore, the need to attune the base case with valid reasoning for meaningful outcomes was essential.

FIGURE 4: (a) 3-D rendering of 4-bedroom house, (b) fuel energy breakdown of the base case model.

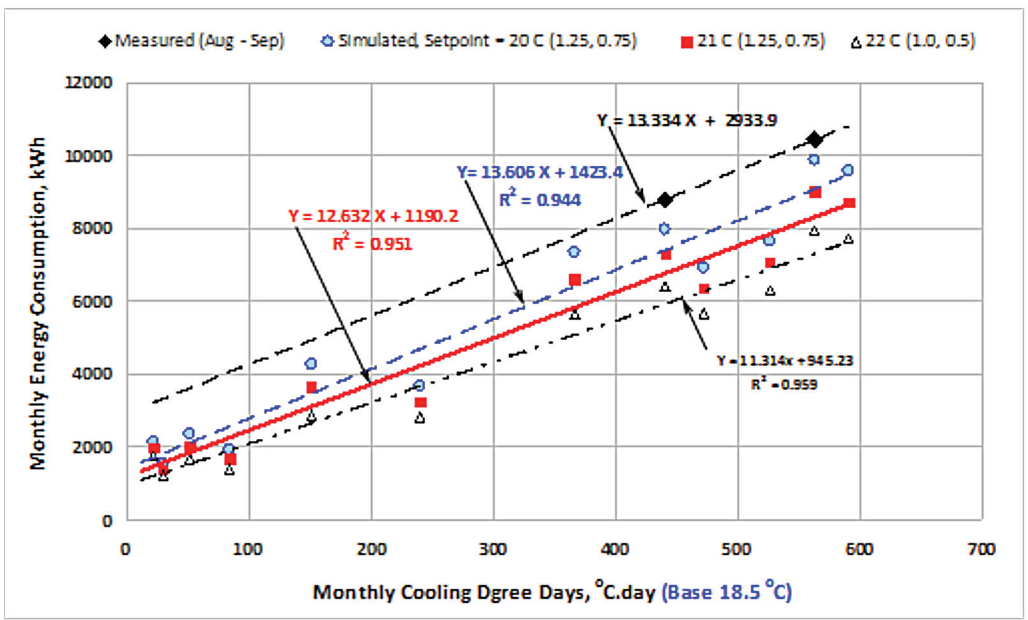


With the aim to verify the total energy consumption and to identify the energy flows and end-use patterns, the energy consumption of a newly built 4-bedroom single family housing unit was recorded. Energy monitors and data loggers were installed and set for data recording. Three energy monitors were used, one for total energy consumption, another for house equipment usage, and the third for HVAC load. The data recorded for lighting energy use was calculated as a difference between the total measured load, and the HVAC and equipment load. 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. The energy data monitoring setup was in operation and under observation during the peak summer months from July through September for a period of approximately three months. This provided the opportunity to validate and attune the base case model with the summer season energy consumption data. Due to the study 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 difference in overall and cooling energy consumption between measurements and simulation results was found to be 24.8% and 27.7% respectively. These seem plausible as a result of three reasons for this variation. Firstly, the house has many rooms with a single set-point control in reality, and all zones have not been modelled for simplicity. Dipasquale et al. [47] discussed the effect of number of zones on the 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%. Secondly, the initial portion of the supply air and return air ductworks were exposed to the outside environment. The third likely cause contributing to the variation is the uncertainty associated with some of the model input parameters. Thus, the house simulation model was attuned based on two different approaches as follows: by considering the correction factor to be the result of heat gain to the exposed supply air and air distribution inefficiencies, and by considering the uncertain input parameters.

Figure 2(b) shows the placement location of the cooling systems at the first floor level. The supply air ductwork originating from the system travels a certain distance before entering the house. Even though the data does specify the insulation of ductwork, one can reasonable assume that there is a considerable amount of heat exchange between supply air and ambient air that has led to higher energy consumption of the house when measured. Figure 5 shows the performance line of the house for both measured and simulated cases with monthly energy consumption on the y-axis and cooling degree days for the year 2012 on the x-axis for a base temperature of 18.5°C. It can be observed that the line representing the measured energy consumption data of the house is convincingly higher than the one for the simulated house model. The y-intercept at x equals zero and defines the non-weather dependent energy consumption in terms of distribution and cooling system inefficiencies and equipment and lighting usage in the house for each case. This value from the performance line and representing the measured data is 7.8 kWh/m^2.month. Considering that the average measured monthly load of equipment and lighting is around 3.1 kWh/m^2/month, the difference partially represents the energy consumption gap of around 4.7 kWh/m^2/month. Assuming an equal share of inefficiencies between the air distribution and the cooling system gives the air distribution inefficiency as 2.4 kWh/m^2/month. Thus, adding this value to the annual overall simulation results gives a reduced difference between the measured and simulated cases with a percentile variation of 15.6%.

FIGURE 5: Monthly energy use vs. cooling degree days (18.5 oC base temperature) for short-term measured consumption, simulated base case model with different temperature set-points and infiltration rate (ACH for ground and first floors as indicated between brackets).



However, considering the uncertainty of specific input parameters it is useful to find answers to the variation in energy consumption between the actual case and simulation model. Parameters such as temperature set-points and setbacks, cooling system operation, and infiltration into the house needed to be re-examined. As the occupants of the housing unit may cool more than necessary, emphasis was given to (1) thermal set-point and setback temperatures and (2) rate of infiltration. Attuning by altering the input parameters is a calibration procedure to approximate the energy consumption results of the simulation model to the measured data [48]. The initial temperature set-point and infiltration for the simulation model for both ground and first floors were 22 ºC, and 1.0 ACH and 0.5 ACH respectively. These were revised to 21ºC and 20 ºC with 1.25 ACH and 0.75 ACH respectively. Table 2 and Figure 6 depict the reduced deviation in each of these cases. The plot for set-point temperature of 21ºC seems appropriate as ASHRAE recommends a variation of at least 10%. Thus, 21ºC, 1.25 ACH and 0.75 ACH input values were selected to represent the base case model parameters. The values for infiltration were assumed based on the number of openings and spatial usage of the house. The ground floor is the living area that consists of an entrance area, a dining room, a study room, a kitchen and a laundry room, and the first floor is the sleeping area consisting of four bedrooms. The first floor occupies less area in comparison to the ground floor. A site visit to the house demonstrated the presence of a large main entrance door at ground level and an absence of doors (i.e. no balconies) at the first level. The only openings on the first floor are the operable double glazed windows. Therefore, infiltration for the ground floor is assumed higher than the first floor with values 1.25 ACH and 0.75 ACH respectively. The final simulation run of the house was carried out and total energy consumption was found to be 162.9 kWh/m^2.yr.

TABLE 2: Attuning by varying uncertain input parameters.

	Overall (kWh/m^2)			
	Measured	Simulated		
		20 C*	**21 C***	**22 C****
Jul	**25.8**	26.8	24.5	20.4
Aug	**28.1**	27.6	25.2	21
Sep	**23.8**	22.0	20.2	17
Total	**77.7**	76.5	69.9	58.4
% Variation	n/a	**1.6%**	**10.0%**	**24.8%**

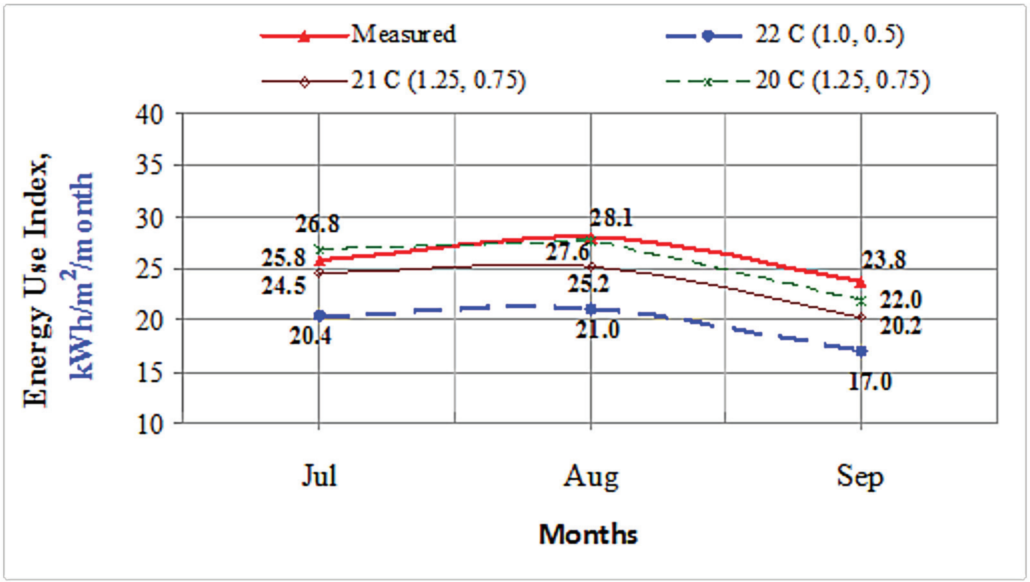
* including revised infiltration; ** Base case before attuning

The results obtained are representative to the housing unit itself and to those housing units that are designed and constructed using the most common design and construction trends in the region, i.e. meeting local standards, including thermal insulation in wall and roof systems, building materials and workmanship. Additionally, the house has a geometry and orientation that is best suited for a hot-humid climate.

5. ENERGY CONSERVATION STRATEGIES UTILIZED

As mentioned earlier, 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. The strategies used, their individual impact on the total energy use, and design elements of the solar PV system to meet

FIGURE 6: Comparison between measured energy consumption and simulation results by revising uncertain input parameters.



a specific amount of the house load are discussed. Seven strategies were utilized with four addressing passive design concepts, two addressing representative codes and standards, and finally one addressing renewable energy (solar PV) as shown in Table 3.

TABLE 3: Energy conservation strategies toward near-Zero energy performance.

Type of Strategy	Strategies Employed
ST-1: Passive Strategies	**ST-1.1:** Green Roof **ST-1.2:** Double Skin Curtain Wall **ST-1.3:** Sloped Roof **ST-1.4:** Insulating Thermal Bridging
ST-2: Code / Standard Compliance	**ST-2.1:** ASHRAE Standard 62.2 **ST-2.2:** Inter. Energy Conservation Code (IECC) 2012
ST-3: Renewable Technology	**ST-3.1:** Solar Photovoltaic (PV)

5.1 Passive Strategies

The objective of the research is to investigate the impact of passive design strategies considering integration with solar PV technology to achieve a near-Zero Energy Home design in a hot-humid climate. The idea is to examine the possibility of achieving near-zero energy performance of a single-family residence through the concepts of Zero Energy Building design.

ST-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 green roof system used in the model is composed of an outer vegetation layer, planting/growing medium also known as soil substrate, polypropylene filter membrane, drainage layer, polyethylene/polythene water proofing/roof repellent membrane, thermal insulation, and roof deck [49]. Many parameters influence the design of a green roof. The green roof system is defined in terms of green roof parameters such as height of plants, leaf area index, leaf reflectivity, leaf emissivity, minimum stomatal resistance, thermal absorptance, solar absorptance, thermal conductivity, specific heat, density, etc. However, the parameters that were found to greatly influence green roof performance are thermal conductivity, specific heat, and density. Information pertaining to the thermal and absorptive properties, and design parameters of the green roof as inputs such as thermal conductivity, specific heat and density, and surface properties have been adopted from appropriate sources in the literature. Hot and hot-humid climates require intensive types of green roof construction. The more intensive the green roof, the greater the depth required for the growing media [49]. Therefore, the outermost layer of the green roof known as the planting media is considered to be 0.3 m (~ 12") deep. A study addressing the measurement of thermal conductivities of leaves of various species can be found in the literature [50]. Measurement results indicated mean values of thermal conductivity within the range of 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 [51]. Specific heat ranged from 1255 to 2267 J/kg-K for fresh leaves and 1514 to 5174 J/kg-K for dry leaves. Similarly, the mass density of fresh leaves was measured to be in the range 475 to 918 kg/m^3 with a slight variation in values for dry leaves of between 336 to 747 kg/m^3. The height of plants and the Leaf Area Index (LAI) have been assumed to be 0.5 m and 5.0 respectively based on the hot-humid climate of Dhahran city. The maximum irrigation rate for the site green roof is considered equivalent in terms of depth of growing media per hour.

ST-1.2 Double Skin Curtain Wall

Double Skin Curtain Wall is a strategy also known as a ventilated wall system strategy and is intended to reduce heat gain through the wall system by venting the cavity with ambient air [52]. The idea facilitating energy performance improvement and thermal comfort enhancement by ventilating the building envelope system could be seen in the Active Dynamic Air Envelope (ADAE) strategy. The ADAE strategy provides the feasibility of actively ventilating the air within the envelope cavities to reduce heat gain in the zone. The 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 was the presence of the wall as the building skin instead of a façade. As the house had 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 the double skin curtain wall system on energy performance. Glazing units on the south walls for both the floors were modelled appropriately. The width of a cavity, 0.3 m, was considered as proposed by (Wong et al. [53]). The double skin curtain wall strategy is not utilized throughout the entire envelope. It is applied to the south façade where potential retrofitting was found to be feasible depending on the house geometry, aspect ratio, and orientation.

ST-1.3 Sloped Roof

Horizontal roofing systems have always been the source of huge amounts of heat gain in buildings, especially in hot climates. Unlike walls and other building envelope systems, the roof is exposed to solar radiation throughout the day. The direct solar beam and the amount of heat gain can be avoided simply by enhancing the roof geometry and tilting it at a certain angle. This enhancement known as sloped roof can also be fruitful when solar energy utilization is of interest. Besides reducing heat gain, in contrast to the horizontal roof, the sloped roof helps yield electricity by harnessing solar radiation when appropriately tilted at a specific angle based on the latitude. The numerical measure of steepness in the form of tilt angle was calculated for the latitude of Dhahran. Figure 7 depicts the construction of the sloped roof. The arrangement demonstrates the limits of both sloped roof and green roof on horizontal roof area.

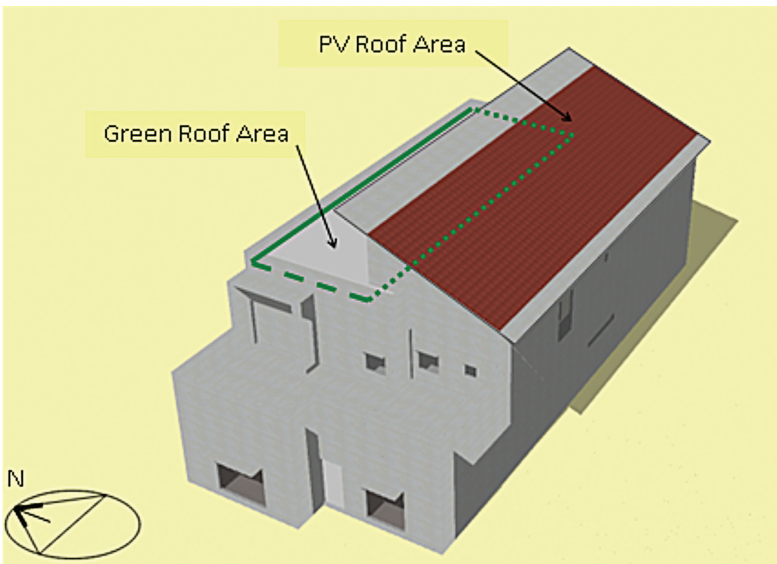
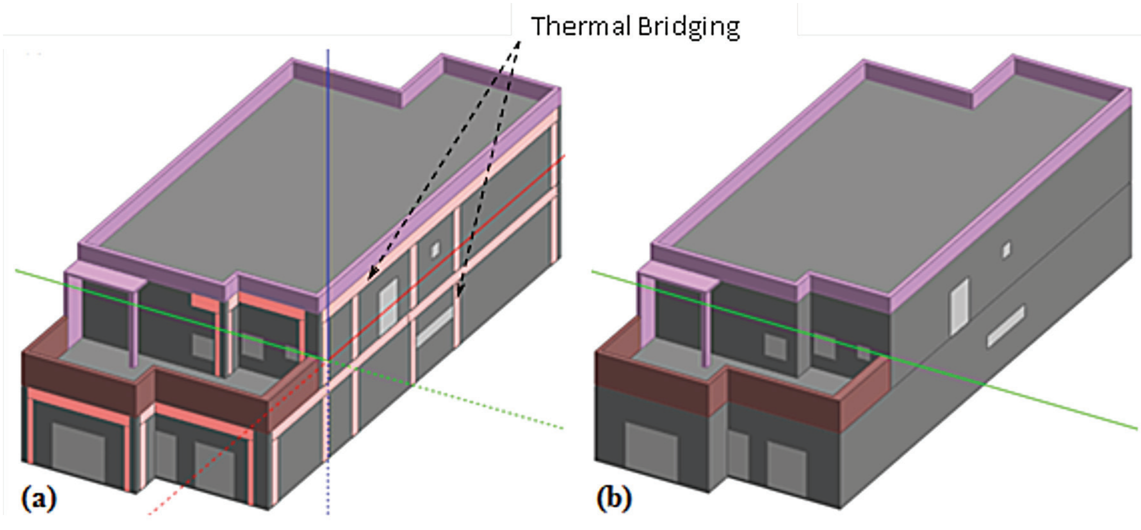


FIGURE 7: 3-D view of the nZEB Model with green roof and PV roof areas.

ST-1.4 Insulation for Wall Thermal Bridging

The sub-surface is an anomaly to the actual construction surface and provides the feasibility of modelling thermal bridging through walls, partitions and sloped roofs. The application of the sub-surface to the development of the base model takes into consideration the heat transfer via thermal bridging into the space through the structure elements such as concrete columns and beams of the house. The wall specifications at the points of location of columns and beams exposed to the outside environment is different in comparison to the actual wall composition. This depicts real life conditions to the heat gains in the space and correspondingly affects cooling energy consumption. Figure 8 shows the placement of sub-surfaces. 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 breaks in the simulation model. An extra thin layer of thermal insulation is then 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.

FIGURE 8: Thermal bridging due to structural elements along the house envelope; (a) model w/ thermal bridging (i.e. sub-surface), and (b) w/o thermal bridging.



5.2 Compliance with Codes and Standards

ST-2.1 ASHRAE Standard 62.2

ASHRAE standard 62.2 (2007) [54] defines minimum required amounts of mechanical and natural ventilation for single or multi-family low-rise residential dwellings. Separate ventilation air requirements, based on floor area and number of bedrooms, are provided by the standard for the whole-building natural or mechanical ventilation. When the whole building is considered, the gross floor area of the base case house is approximately 377 m^2 (Category: 279.1-418 m^2) with more than seven rooms. This gives an approximation of the outside air requirement of 57 L/s. Similarly, the outside air requirement for both ground and first floors has been found to be 35 L/s from the floor area category: 139.1-279 m^2. The ventilation air requirement calculated for the house and its zones based on ASHRAE standard 62.2 was therefore found to be 5.0 L/s-person for both ground and first floors.

It should be noted that the ASHRAE standard 62.2 specifies a complete set of requirements for the design of ventilation system by addressing whole-building ventilation rates, ventilation types, ventilation control strategies, and duct design. This can't be neglected as the ventilation rates specified by the standard must somehow be met by the type of ventilation and ductwork being used in the house. The research, however, only looked into the implications of using the prescriptive ventilation rates of the standard on energy. Detailed design may be considered at a later stage.

ST-2.2 International Energy Conservation Code (IECC)

The International Energy Conservation Code (IECC 2012) [55] 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. Table 4 indicates the U-values of envelope system of base case model and compares them with the U-values of the corresponding systems as specified by IECC 2012. From the table it can be seen that the roof and floor systems had U-values higher than the prescribed IECC 2012 requirements. Thus, these systems were better thermally due to the presence of construction elements. The ground floor of the base case model was not thermally insulated. The roof did have insulation but failed to meet the prescribed IECC 2012 requirements. Hence, a layer of thermal insulation was added to the ground floor and the roof was replaced by a massive one with a low U-value based on the supporting literature [56]. This strategy definitely proved worthy for the base case model with thermal bridging through columns and beams along the envelope construction. The enhanced construction assemblies of the envelope systems are presented in Table 5.

TABLE 4: Thermal specifications of envelope systems of the base case model vs. IECC 2012.

Envelope System Type	**U-value (W/m^2-K)**		Envelope System Enhancements
	IECC 2012	Base Case	Revised Base Case
Walls	1.89	0.466	× Not required
Roof	0.189	0.539	✓ Required
Windows	2.839	2.709	× Not required
Ground Floor (Slab on Grade)	0.437	0.792	✓ Required

TABLE 5: Summary of enhanced construction features of building envelope components.

Envelope System Type	**Layers** (Outside to Inside)	**Thickness (m)**	**U-value (W/m^2-K)**
Walls {modified to overcome Thermal Bridging}	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 {modified to meet IECC 2012 requirement}	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	
Ground Floor {modified to meet IECC 2012 requirement}	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	

Though the replaced roof system met the IECC-2012 requirements, it still fell under the umbrella of traditional building practices. Where IECC 2012 is a prescriptive yet mandatory requirement, a green roof is innovation as well as a step further toward sustainability. This was the major reason for considering a green roof over IECC 2012 compliant roof insulation level. The green roof modelled has a U-value of 0.433 W/m^2-K. The IECC compliant roof has a U-value of 0.189 W/m^2-K. Therefore, simulation runs of both roof systems and the literature review helped to define the effect of each strategy on energy performance of the house. Results are tabulated in Table 6. From the table it is clear that a green roof is more energy efficient than an IECC 2012 compliant roof. This is due to the fact that a green roof has thermal mass in the form of soil substrate over 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 [57]. High rates of evapotranspiration draw heat out of a building as a result of wetness in the 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 also reduced cooling energy but could not perform quite as well as the green roof due to the absence of evapotranspiration. Another reason behind better performance of the green roof is the albedo [58]. Castleton et al. [57] defined albedo as the ratio of total reflected to incident electromagnetic radiation and the higher the albedo the better. According to Gaffin et al. [58], albedo of a 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, green roofs address sustainability by providing biodiversity, stormwater retention and quality, improved acoustical performance, structural integrity, etc.

TABLE 6: Annual energy performance of green roof vs. IECC 2102-compliant roof.

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

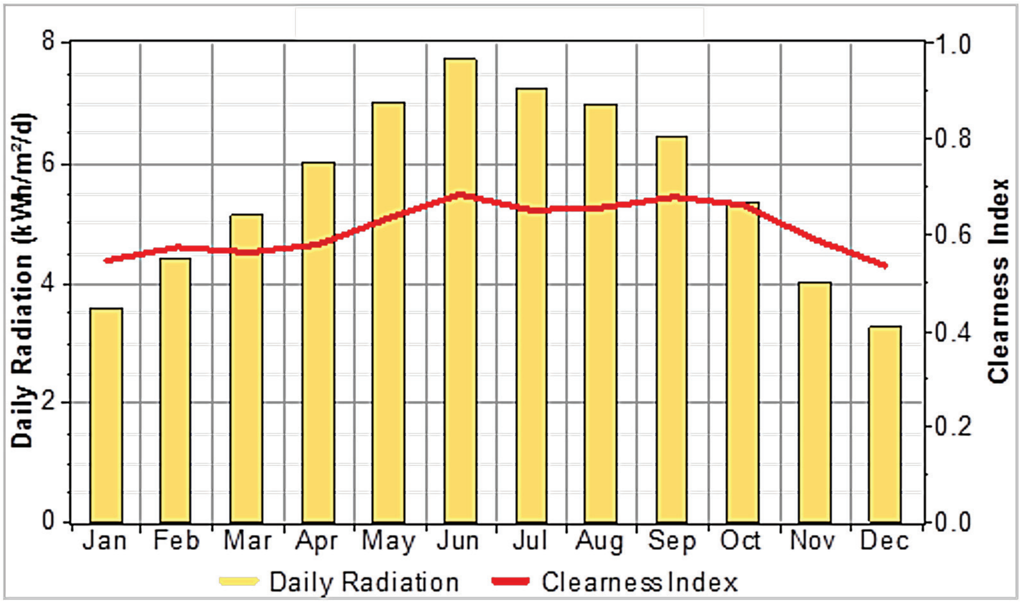
5.3 Renewable Energy

The last of the strategies in reducing the energy demand of the house was to reduce its dependence on the electricity grid by addressing electricity production in the form of solar photovoltaic (PV). Relevant sources 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 can be observed for the base case model in section 3.3 where cooling energy is around 79% of the total energy end-use. The remaining energy is shared by equipment, general lighting and exterior lighting. Thus, meeting at least the remainder of the energy through solar PV to offset the grid dependence for this part of the house load was found to be a viable option. The daily energy end-use simulation result of equipment and lighting is approximately 28.7 kWh for an average representative day of each month [59]. 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 needs 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. The following steps discuss the procedure to calculate the land area requirements based on the availability of solar resource and worst scenario for a PV system to meet the daily electricity load.

1. *Determination of daily energy requirements in kWh*: The electrical load PV system has to meet each day.
2. *Determination of system design load*: Load based on the efficiency of the PV system. It can be calculated as:
   Design electrical load (E_D) = (Daily Energy Requirement) / ηPV_{System} (1)
   where ηPV_{System} is efficiency of the 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.
3. *Solar radiation needed*: Amount of solar radiation needed to meet daily energy requirement.
   Solar radiation needed ($E_{Solar\ Rad.}$) = E_D / ($PV_{Panel\ conversion\ efficiency}$) (2)
4. Land area requirements: Minimum area required for PV to produce and meet daily electric load
   PV required area = $E_{Solar\ Rad.}$ / Daily Solar Radiation (3)

Area required is a function of daily solar radiation incident at a particular location. Figure 9 shows the average daily global horizontal radiation for each month for Dhahran. The solar radiation data was obtained from the NASA surface meteorology and solar energy website (NASA SSE, 2013) [60]. From the figure it can be observed that maximum radiation is incident in June and minimum in December. For the worst scenario, the lowest amount of daily solar radiation is considered for year-round use. A system meeting the daily energy requirements on an average representative day in December will meet the same when the solar radiation is higher during the rest of the months. Applying the equations mentioned above, an area of 97.2 m^2 is required to successfully satisfy the lighting and equipment loads of 28.7 kWh/d when a PV panel with a conservative conversion efficiency of 15% is used. However, PV technology and power output (Wp) of PV modules can be greatly affected by the area in which it is deployed. The availability of the sloped roof area of the house to meet the calculated land area requirements for PV was checked. Modifications to the sloped roof were made accordingly. Having calculated the land area requirements of PV, the system was systematically designed using HOMER based on equipment and lighting loads of the base case model, tilt angle, solar resource availability and system costs. HOMER is a hybrid micro-power optimisation model that carries out a number of sensitivity analyses and identifies cost-effective solutions to energy requirements [61]. Lau et al. [62] carried out performance analysis of hybrid PV/diesel energy systems under Malaysian conditions using HOMER. Another feasibility study was conducted to replace the diesel generators with wind farms, PV and hydrogen production systems using HOMER [63]. Shaahid and Elhadidy [64] at the Center for Engineering Research at KFUPM presented their findings on the economic analysis of hybrid power systems for residential loads in hot climates. Application of gen-sets in small solar power systems was also carried out to meet a certain amount of daily load using HOMER [65]. 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, the latter characterises the associated components such as PV, converter and battery.

FIGURE 9: Average daily global horizontal radiation and cloud cleanness index during each month (based on hourly average values) for Dhahran (Source: HOMER).



Hourly simulation results of a day were input to the HOMER model. Information with respect to PV array sizing includes cost, lifetime, slope, azimuth, and derating factor of the array, as well as ground reflectance and temperature effects. The cost for 1 kW of output was considered to be \$5000 [66]. This includes shipping, tariffs, installation, and dealer mark-ups. The array was assumed to function for a lifetime of 25 years. The slope of the array was approximated using the latitude of Dhahran and set as 23.7° [67]. A study [68] on optimum PV tilt angle was carried out for the latitude of Madinah. The optimum tilt angle was found to be different throughout the year and the average tilt angle yielded a slope slightly less than the latitude. The study concluded yearly average panel tile angle of 23.5° in comparison to the 24.5° latitude of Madinah. The derating factor for PV is the scaling applied to take into consideration the reduced output as a result of shading, dust, etc. The value of 0.9 was assumed which means the array output is 10% less than actual. The effect of temperature on an 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. A 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 numbers of batteries were considered for the model to make the optimal choice. An inverter intended to convert the DC electricity of PV to AC for household application was also required for which a capital cost of \$900 per kW was considered assuming that it would not require any sort of maintenance. Inverter efficiency of 90% and a lifetime of 15 years with capacity variations from 3.5 kW to 4.5 kW were supplied to the model. This completed the development of the renewable energy model for the current phase of study. Technical data assumed for the system components is presented in Table 7. 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**.*

TABLE 7: Technical data of the selected PV system components.

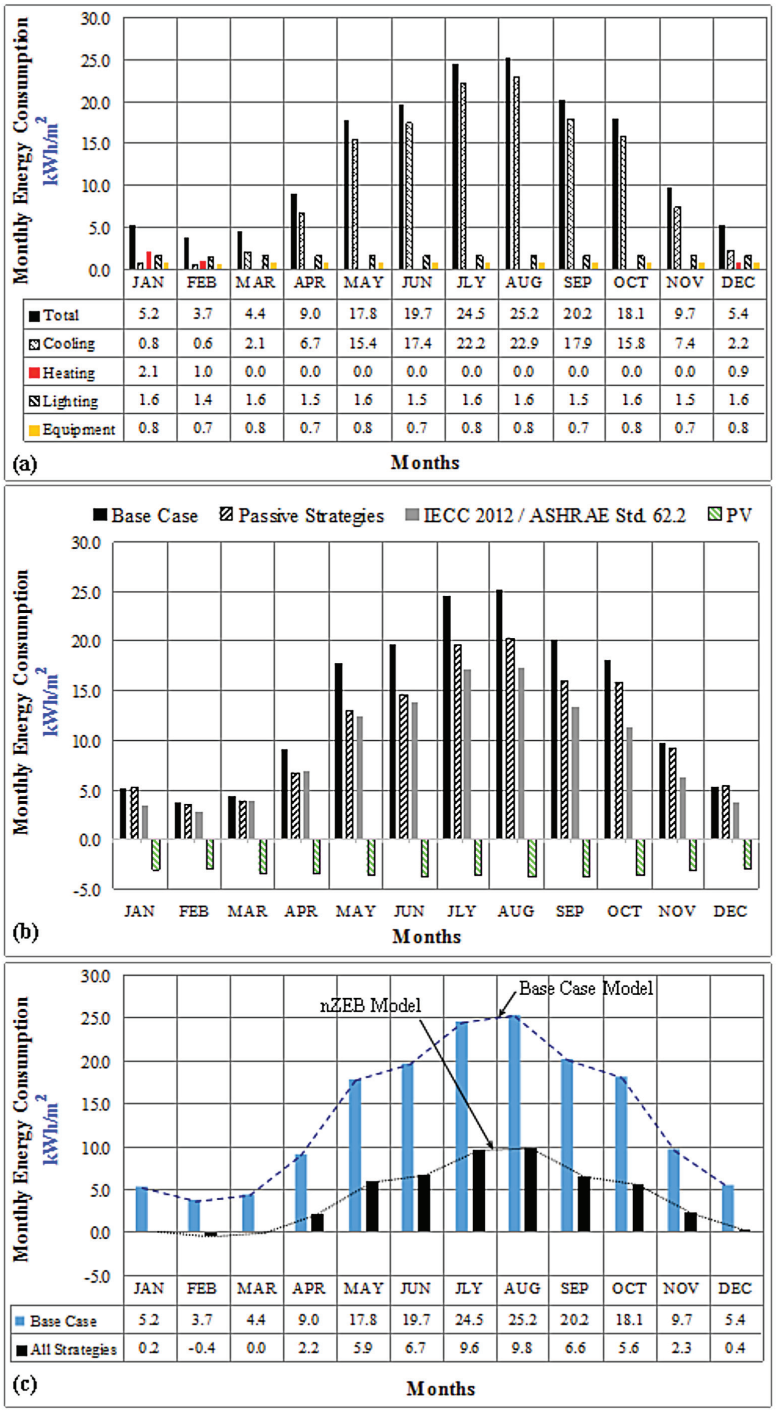
Description	Data
PV	
Sizes	8.1-9.5 kW
Capital Cost	$ 5000/kW
Lifetime	25 years
Derating Factor	0.9
Slope	23.7^o
Inverter	
Sizes	3.5-4.5 kW
Capital Cost	$ 900/kW
Replacement Cost	$ 600/kW
Lifetime	15 years
Efficiency	90%
Battery	
Type	Trojan L16P
Nominal Voltage	24 Volts
(4 batteries per string)	
Nominal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

6. RESULTS ANALYSIS AND DISCUSSION

6.1 Performance Evaluation of Base Case

The developed and attuned base case model of a single family 4-bedroom university faculty housing residential unit was simulated using the 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 10(a). A total of 162.9 kWh/m^2 of energy is consumed by the base case model annually. It can be observed that August recorded a monthly high of 25.2 kWh/m^2 and February a low of 3.7 kWh/m^2. The literature cites various techniques to evaluate the energy performance of a building. Different indicators were and are still internationally under development [69]. 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 an energy signature make it possible to evaluate the performance of a building. Performance lines plot monthly energy use against monthly degree day totals [70]. The procedure is therefore applied to assess the energy performance of the base case. The slope of the line describes the amount of heat gained in the zone through the building envelope and points define the accuracy of the fit with the line. This gives an understanding of how well the building performs. The closer the points are to the line, the better the correlation and building performance. The accuracy of the fit is represented by an R value regression coefficient. The fit for the base case was around 0.98.

FIGURE 10: Monthly energy consumption of base case (a) total and segregated, (b) as a result of annual simulation of each set of strategies, (c) monthly energy use index of the nZEB model .compared to base case model.



6.2 Combination of Strategies

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 in the zones through the building envelope can be reduced with proper selection of strategies. For the purposes of this study, the strategies utilized are comprised of a combination of passive techniques, code and standards, and renewable energy technology. Each one is unique in the way that it has been applied to a house in a hot-humid climate. Table 8 shows the energy consumption reductions as a result of each energy conservation strategy as well as a combination of all strategies. From the table, it can be understood that each strategy played its part in reducing the energy use intensity to its lowest potential. A green roof and double skin curtain walls were new to the climatic zone and conserved 5.1% and 6.1% of energy use respectively. The availability of sloped roofing systems in dwellings in Dhahran showed potential in decreasing heat transfer and correspondingly cooling energy. For the house model under investigation, the sloped roof saved 1.1% in energy use. As pointed out earlier, allowing thermal break throughout the envelope does have a potentially negative impact on building energy use. Insulating the thermal breaks in the housing envelope resulted in 7.8% savings of the energy use. Though each strategy had its impact on energy use individually, a set of strategies proved effective 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 10(b). An energy consumption reduction of 17.2% was achieved by only implementing passive strategies in the model. The importance of codes and standards can best be understood at this stage. Though the walls and windows of the house envelope system already complied with IECC 2012 R- and U- value requirements respectively, insulating the wall thermal breaks did make a significant effect on the house energy use (7.8%); but the implementation of ASHRAE standard 62.2 clearly produced great energy savings. Both ASHRAE standard 62.2 and the IECC 2012 together reduced the energy consumption by

TABLE 8: Reductions of annual energy consumption.

Energy Conservation Strategies		Energy Consumption (kWh/m^2.yr)	Energy Consumption Reduction (%)	Energy Reduction (combined) (%)	
	Base Case	162.9	-		
Passive Strategies	Green Roof	154.6	**5.1**	**17.1**	**46**
	Double Skin Curtain Wall	152.9	**6.1**		
	Sloped Roof	161.0	**1.1**		
	Insulating Thermal Bridging	150.1	**7.8**		
Code / Standard	ASHRAE Std. 62.2	113.0	**30.6**	**31.1**	
	IECC 2012	157.5	**3.3**		
Passive Strategies + Code / Standard		**87.9**			
Renewable Energy	Solar **PV**	Energy Production = **40.2**	**24.7%**		
Combination of Strategies		87.9 - **40.2** = 47.7	**70.7%**		

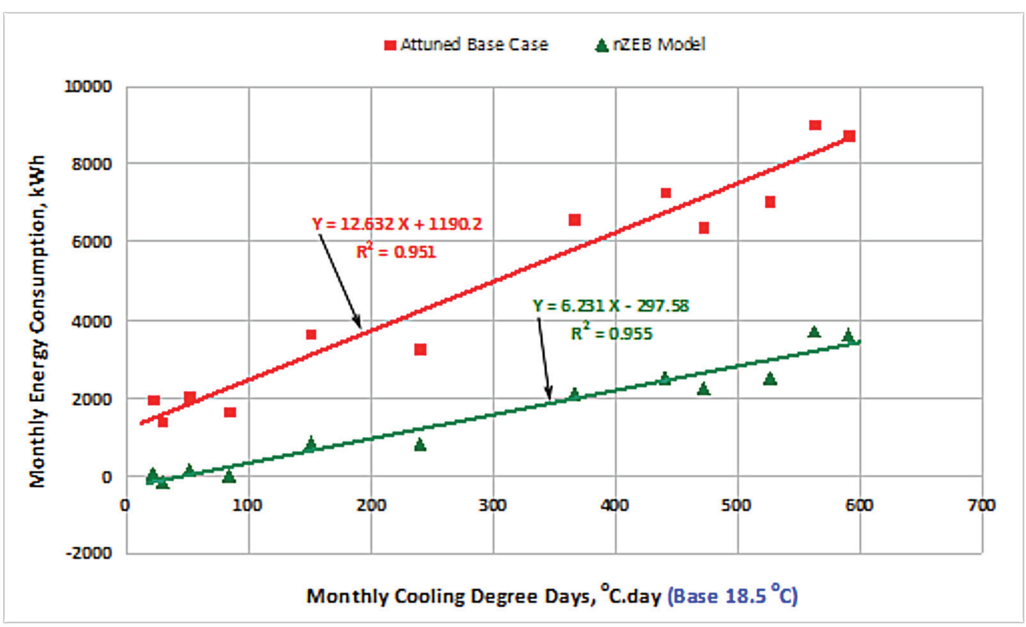
approximately 31.1%. The PV system used over sloped roof succeeded in harnessing solar energy, helped meet the equipment and lighting energy demands, and partially compensated grid involvement by meeting approximately 25% of the reduced energy demand of the house.

6.3 Performance Evaluation of nZEH Model

The influence of all strategies on energy performance of the house and performance of the new design in terms of the characteristic concept of Zero Energy Building (ZEB) is discussed. Figure 10(c) 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 has been calculated to be 47.7 kWh/m^2 with a total percentile reduction of 70.7%. It can also be noted that the winter months, i.e. January, February and December, have very low energy use as cooling is at its minimum during these months, and only lighting, equipment, and heating primarily contribute to the energy consumption. The PV system being able to meet the lighting and equipment load has helped provide the house with 28.7 kWh/m^2/month of electricity and an additional extra electricity production depending on the availability of the solar resource. This has not only reduced gross monthly energy consumption during the winter season but has also partially offset the remainder electricity requirement from the grid. Implementation of the strategies depicted has had a great impact on cooling energy use during the summer season. The energy performance of the nZEB model has then been studied by employing the same approach as done for the base case model. The procedure of performance lines has therefore again been applied to assess the energy performance. Figure 11 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 the best fit to performance points.

It is evident from the plots that the slope of the performance line of the nZEB model is less than the slope of base case line. This unmistakably signifies that heat gained in the zones

FIGURE 11: Energy performance line of the nZEB model.

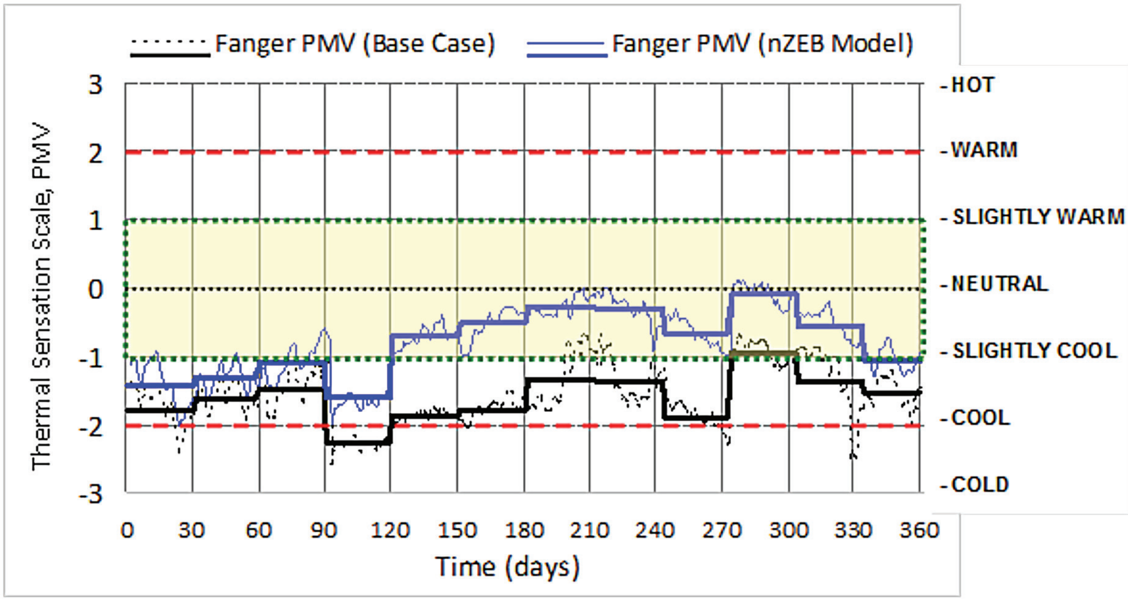


and energy consumed by the nZEB model for the required number of cooling degree days is less than the base case model. Scatter of data points additionally strengthens this point. The points of the nZEB model seem much more closely packed to the line and depict an improved fit over the base case. Thus, the correlation of data points with the performance line for the nZEB model is better than its counterpart demonstrating better energy performance. Owing to the distribution losses, the performance line of the nZEB model, at the moment, is unable to explain the non-weather dependent energy consumption. This, being one of the major limitations of this study, is due to the fact that 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 the 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 lower slope value with the data points more closely packed indicating an 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 the energy performance have developed interest in assessing the thermal comfort of nZEB house model. PMV analysis suggests the plot between time and thermal sensation index be within the limits of -1 and +1. The nZEB model, as shown in Figure 12, has depicted great improvement over the 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. Thermal comfort which was only achieved during a few weeks in the 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 the strategies mentioned into the base case model. Influence of one strategy alone on thermal comfort did not show much of a variation except green roof, sloped roof and thermal insulation of the ground floor. 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 in the house but slightly increased the energy consumption.

6.4 Cost-Economic Aspects of PV System

The design of a PV system using HOMER has led to optimized 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. A techno-economical assessment of PV in a residence in Jordan was presented by Al-Salaymeh et al. [71]. The payback period was calculated based on various economic factors. Results for the 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 [72]. Governmental subsidies for offsetting fossil-fuel electricity, capital cost subsidy for renewable sources, 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 a similar trail for the assessment of payback period. Table 9 presents the considerations for calculation

FIGURE 12: Thermal comfort assessment of the nZEB Model using Predictive Mean Vote (PMV).

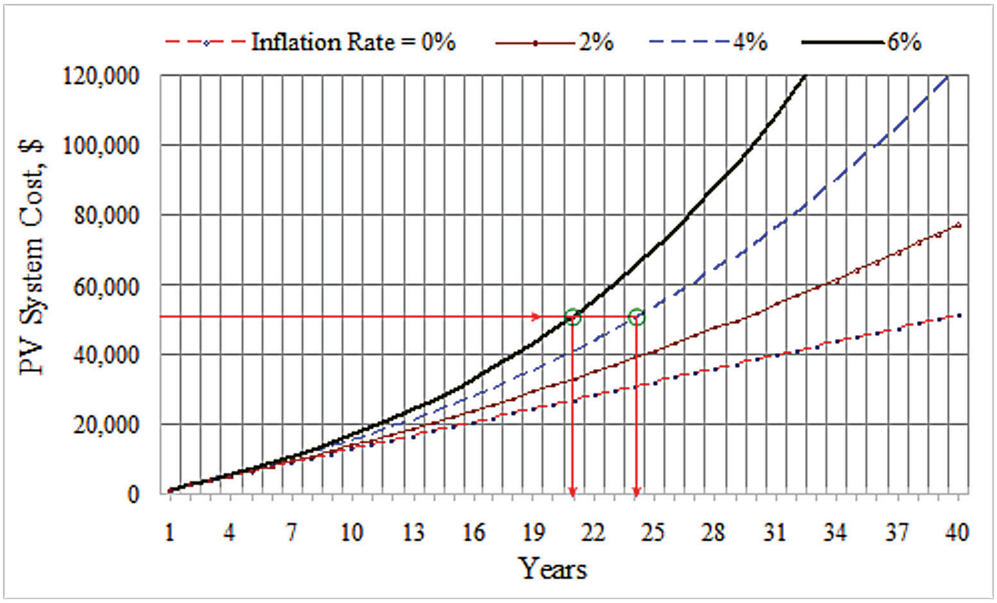


of payback period for the designed system. Considerations to calculate the payback period are reflected in the table. Offsetting fossil-fuel electricity, renewable energy cost credits, and other financial incentives have all been assumed in the form of government subsidies. Therefore, the payback period for different considerations based on total system cost is depicted in Figure 13. The calculation clearly signifies that solar PV can only be feasible in Saudi Arabia if the government takes an 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% government subsidies of total PV system cost in the form of government subsidies. Figure 13 indicates a decline in number of payback years upon considering increasing inflation rates. The proposed cases meet the payback period in less than the assumed life cycle of the system. The costs do include end of life replacement costs associated with system components and operation and maintenance costs. This analysis therefore includes 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 per unit kW of power.

TABLE 9: Reductions of annual energy consumption.

Parameter	Magnitude
Annual energy consumption of nZEB model w/o PV	33,978 kWh
Annual energy production (adjusted based on real life conditions by HOMER)	15,392 kWh
Annual energy consumption of nZEB model w/ PV	33,978 - 15,392 = **18,586kWh**
Saudi Arabian electric energy rate	SAR 0.26 / kWh = **$ 0.069 / kWh**
Annual electricity bill	18,586 × 0.069 = **$ 1282**
Annual inflation	0%, 2%, 4%, 6%
Governmental subsidies	**50%** of total system cost

FIGURE 13: Estimate of payback period considering different inflation rates with 50% governmental subsidy..



7. CONCLUSIONS

7.1 Achieving Near-Zero Energy Performance

The research initiative taken up represents the first initiative carried out in Saudi Arabia. This was done to evaluate the near-zero energy performance of an existing 4-bedroom single family dwelling at KFUPM with the help of the state-of-the-art energy simulation program *DesignBuilder* and energy consumption monitoring. The idea behind the innovative concept of ZEB resulted in investigating best passive design strategies, utilization of relevant codes and standards, and solar PV technology working in tandem to achieve an nZEH design in Saudi Arabia. The work carried out was divided into three phases. The first phase provided insights into studies related to ZEB design highlighting relevant concepts and requirements. This included the investigation of proper passive strategies and their impact on energy consumption, the effect of relevant codes and standards, use of PV technology to offset a specific amount of load from the electricity grid, and review of BPS programs and selection based on modelling capabilities in the light of ZEB design concepts. As the research focused on enhancing the performance of an existing house, the second phase emphasized the base model development and attunement 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, sloped roof, insulating for thermal break, International Energy Conservation Code 2012, ASHRAE standard 62.2, and solar PV. Energy performance indicator kWh/m^2/yr was utilized to assess the impact of each strategy. Thermal comfort analysis was also performed. Personal and environmental factors of thermal comfort were given consideration in thermal comfort analysis by using Fanger's predictive mean vote model on the thermal sensation scale throughout the year. Simulation results of the base case model of the house calculated a total energy consumption of 162.9 kWh/m^2/yr 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. The 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 a few weeks in summer and late fall. The simulation results of the house model depicting ZEB concepts and predicted a total energy consumption of 47.7 kWh/m^2/yr. The PMV curve showed a significant shift towards the thermal comfort index on the thermal sensation scale. The research conducted seems appealing at one instance but suffers from non-integration of solar PV. The sloped roof of the house is sloped at an optimum angle of 23.7°. It is assumed that PV panels are arranged over the sloped 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 benefits it provides, for example, 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 this study, a brief discussion on it may suffice to enhance its prospect for application. Surface temperatures of PV modules reach a high of 80°C in summer. The 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/m^2 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 the DHW demands of the house.

7.2 Toward Zero Energy Performance

Around 70% reduction in total energy consumption has been achieved by only implementing the strategies discussed earlier. Various other strategies such as solar cooling technologies, energy efficient lighting systems, equipment and HVAC system, and control systems were not considered. The nZEB house model, especially in light of unexplored strategies, holds 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. The house, therefore, should not only be energy efficient but also water efficient. Green roofs require 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 evaluated for energy conservation. Additionally, occupant education about the technologies used in the house does have a great influence. The careful and responsible behaviour of occupants will help keep energy usage trends to a minimum.

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