The Potential of Solar Energy in Saudi Arabia: The Residential Sector

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Abstract

Saudi Arabia is considered one of the largest oil consumer countries. The country's contribution to global warming is continuously growing; local consumption of electrical energy is high and the demand is rapidly increasing. Based on the Kingdom's current energy status and its future plans, solar energy is shown as an attractive alternative, ample, reliable and clean resource for sustainable development. This study, review and investigates the potential of implementing solar energy into the Saudi residential sector by optimizing the integration of PV technology into buildings. The study field is confined to the typical Saudi house. Different BIPV placement methods were proposed and investigated through varied cases. Every case was parametrically tested solo in site so its highest energy potential could be measured first, creating a comparative baseline for its potential within the neighborhood-tested scenarios. The resulting impact was measured and analyzed through the measures of energy generation and consumption.

1. Introduction

The Kingdome of Saudi Arabia is characterized by its strategic geographical location on the sun-belt, meaning, its exposure to a huge amount of direct normal irradiation (DNI), on average 2200 kWh/m2 annually; this is considered one of the highest in the world and is twice the average radiation in Europe (Al-Shehri, 2010). This abundant amount of renewable solar energy resource should be exploited in the light of global warming crisis; where currently the world is exhausting fossil fuel resources at an alarming rate to produce energy which is causing vast pollution around the globe. In fact, Saudi Arabia is one of the highest GHG emitting countries in the world as it depends on the burning of petroleum to meet the annual increase in its electrical demand and is therefore contributing to world climate change. It is essential to move towards renewable resources in order to mitigate the effect of global warming, using sustainable approaches to conserve future resources and achieve the environmental demand for clean living.

Solar energy is an unlimited clean resource for electricity generation: the effectiveness and operational efficiency of using photovoltaic (PV) systems to harvest it have been proved by small scattered projects throughout the Kingdom since the 1970s; these have demonstrated its suitability for the local climatic conditions. It has been found promising for future use and to have many advantages and huge economic benefits. The kingdom's energy consumption is aggravated by the annual increase in population, which in turn makes the residential sector the largest consumer of local energy, consuming more than half the country's annual production of electric power. In the developed world, buildings alone consume one half of the globe's produced energy. The incorporating of PV arrays within the fabric of individual buildings (rather than large-scale projects, such as solar plants) could be beneficial in that matter for both consumers and the country. The dissemination of PV technology could engage people in contributing to overcoming environmental concerns, while supporting the electrical utility grid during the peak hours of demand.

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Serious consideration should be given to expanding the application of these systems in finding appropriate solutions that can be incorporated into the operation of buildings, and especially the residential of them. Furthermore, it is considered an additionally attractive solution where it can enhance the appearance of buildings in innovative ways and provide inspiration for high architectural quality. Adapting a harmonized overall appearance depends on how the building integrates photovoltaic (BIPV) systems into the sun-exposed envelope surfaces, which represent the interface between internal and external environments of buildings. Being defined as an alternative multifunctional element, replacing other elements of the building envelope, the BIPV can be added as a construction material or an architectural component that replaces a conventional one or acts as a new one.

The integration level could range from a system hidden on the roof, to a modest shading component, to a leading element in the building appearance. The optimization of the BIPV addition depends on many effectual parameters that must be considered in deciding how to provide the highest yield from solar radiation that reaches buildings' exposed surfaces. This study discusses the BIPV potential in generating electrical power for the Saudi residential sector.

2. Significance of Implementing BIPV Systems in the Saudi Residential Sector

The demand for electricity in Saudi Arabia is increasing by an annual growth rate of 5.8% (Ministry of Water and Electricity, Office of the Deputy Minister Information & Statistic Centre., 2007) this is due to many factors, such as the rapid economic development, a growing population, low electricity prices and the absence of energy conservation measures (Al-Saleh &Taleb, 2010). In 2008 the country consumed 35 GW and was incapable to meet all the demand during peak hours, so there were power shortages in some areas; that amount is anticipated to grow to 70 GW by 2023 ("The KICP Annual Strategic Study: Saudi Arabia Solar Energy Manufacturing and Technology Assessment," 2009). Obviously, this contributes in the exhausting of fossil fuels to produce more energy, which consequently raises environmental concerns. There is a great national need to develop alternative sources of energy which are friendly to the environment and which could readily meet the country's future demands in the post-oil era. This calls to find some substitute plans to cope with the ever-increasing statistics. Accordingly, this study's importance represents in its area of investigation for being focused on the residential sector (the highest consumer of local energy) to find the potentials of solar energy applications in households through using BIPV technology, and if it can be an energy alternative in the future; and to anticipate the prospects of creating mutual benefits between the energy consumers and the country. It also attempts to encourage the investments in renewable energy locally in means of expanding the market opportunities and reducing the greenhouse gases (GHG) emissions to support the country's sustainable development plan. Furthermore, this study seeks to observe any alterations in future local architecture where this technology is integrated as a construction element, while examining this project process on different levels.

3. Electrical Energy Consumption

The generation of power has always accounted for a large portion of the Saudi energy demand (Liu, Tellez, Atallah, & Barghouty, 2012). In fact, 79% of the domestic electrical power is consumed by buildings; HVAC has a very high demand for power, given the severe weather in most regions. That percentage is divided between commercial, governmental and residential buildings, but the last is by far the highest energy consumer of all building type (Al Ghabban, 2013). On a world scale, recent analyses of energy consumption by national residential sectors compared to all other consuming sectors varies between 16 and 50% in different countries, with an average of about 30% worldwide, as shown in Figure 1; however, Saudi consumption is found to be the highest, consuming over 50% (Saidur, Masjuki, & Jamaluddin, 2007). In 2007, the electricity consumed by the Saudi residential sector was more than the sum of all the other sectors in the country. It accounted for about 53% of total energy consumption, amounting to 181.1 billion kWh(Ministry of Water and Electricity, Office of the Deputy Minister Information & Statistic Centre., 2007); and this high amount still applies currently. A percentage breakdown of energy consumption by sector is illustrated in Figure 2.
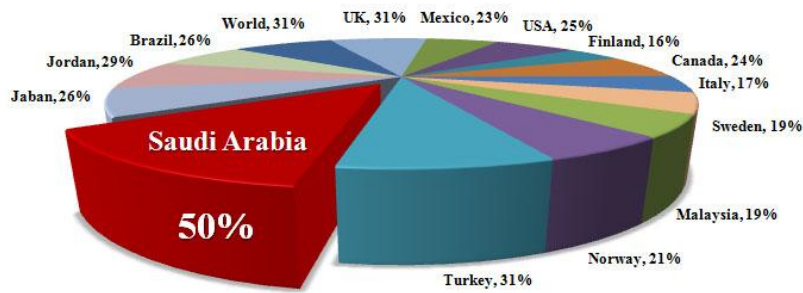
Figure 1: Saudi Arabia residential sector energy consumption compared to international consumption in the same sector [7].

Over the past four decades, Saudi Arabia has undergone rapid population growth and economic development, coupled with a rapid increase in electricity demand and low tariff prices (Al-Naim, Numan, Alshaibani, & Almaziad, 2001)(M. Y. Numan, Al-Naim, ALSHAIBANI, & Al-Maziad, 2000). Statistical data shows that peak loads reached nearly 24
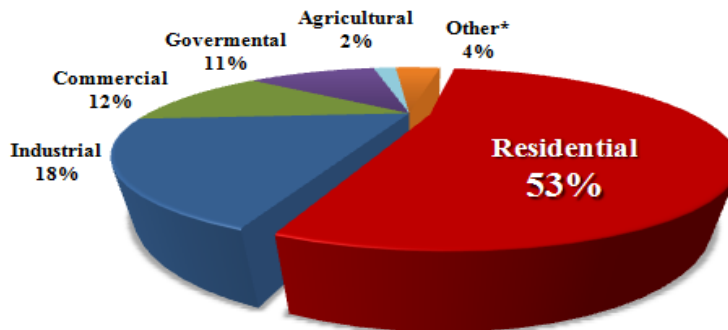
* 'Other' includes hospitals, mosques, street, and charities.

Figure 2. Distribution of Saudi electricity consumption in 2007 by consuming sector(Ministry of Water and Electricity, Office of the Deputy Minister Information & Statistic Centre., 2007).(that is, 25 times their 1975 level), and are expected to triple that amount by 2023 under the absence of energy conservation measures (Al-Ajlan, Al-Ibrahim, Abdulkhaleq, & Alghamdi, 2006). Over the last few years, electric power consumption has increased even more, at an average annual rate of 5.8%.GW in 2001. Forecasts for the coming years indicate that the number of subscribers in the residential sector alone will grow by 2.1% on average annually (Ministry of Water and Electricity, Office of the Deputy Minister Information & Statistic Centre., 2007). This consumption's rapid growth contributes to increasing the pressure on electrical demand; if this continues, it would be necessary to double production capacity approximately every ten years. Measures to rationalize consumption did not achieve the desired amount; consequently there is an urgent need to develop energy conservation policies and find alternative energy sources for future sustainable development (S. A. Al-ghamdi, Al-gargossh, & Alshaibani, 2015; Al-Maziad, Numan, Alshaibani, & Al-naim, 2002; K. Alshaibani, 2001; K. A. Alshaibani, 2008; M. Numan, Alshaibani, Almofez, & Almazyad, 2011; M. Y. Numan, Ashaibani, & Almaziad, 2014).

3.1 Electrical Energy Conservation and Sustainable Development

In a near future drained of natural resources, Saudi Arabia is considered the second among the five countries in the world with the largest oil reserves, with about 21% of the global total of proved reserves of oil; where the reserves to production ratio (R/P) for the crude oil lifespan is forecast to be around 69 years. Moreover, the country has the fifth largest R/P of natural gas of about 81 years(*World Energy Resources: 2013 Survey*, 2013). Yet with less than 100 years of fossil fuel energy reserves, the country needs to establish alternative inexhaustible clean sources to invest in and rely on so that it can meet its tremendously growing power demands through the post-oil era without affecting the economy but also maintaining sustainable approaches.

Measures have been taken to meet the electrical consumption concerns through many projects on different levels under the surveillance of the Ministry of Water and Electricity; and to find some methods of coping with this ever-increasing statistic. In 2008, the National Campaign for Electric Consumption Guidance was launched to spread awareness of ways of rationalizing power consumption among citizens ("The National Campaign for Electric Consumption Guidance," 2009). On another level, there are larger projects that have been implemented to provide huge technical and economical benefits, like the interconnecting of the electrical grid to the Gulf Council Countries (GCC) network; this step was taken in a larger perspective with the additional plan to be grid-connected with other Arab countries in the future. Furthermore, the ministry cooperated with different bodies in many researches/studies (conducted and ongoing) which are concerned with the electricity consumption issue in general. Several of them investigate where the buildings are involved; i.e. the standards of electrical appliances, materials specifications, Construction characteristics (Ministry of Water and Electricity, 2013).

Energy strategies in all dimensions have always been of great importance in the country's development plans. In the Ninth National Development Plan (2010–2014) the challenges were even higher in establishing the pillars of sustainable development; whilst minimizing demand on power, rationalizing the exhaustion of natural resources, protecting the environment and expanding the investment opportunities in the global market of renewable energy ("Brief Report on the Ninth Development Plan. Riyadh," 2009).

4. BIPV Modelling Computation

Estimating the solar energy potentials of buildings depends on multiple correlations of the parameters and variables concerned, then testing to identify their impacts on the energy performance. Therefore, empirical quantitative methodology was pursued to investigate and analyse the study goals, relying on experimental method through employing two research tools: the collecting of substantial data and then simulating them. The Energy Plus package is adopted as the simulation software in this research. It offers considerable flexibility, a vast amount of detail and extensive documentation that enhances its accessibility.

Energy Plus has three different models to predict the electricity produced by PV: the simple, the equivalent one-diode and the Sandia models. All models allow PV modules to be integrated into surfaces of the building envelope in the Energy Plus model. The implementations of these PV models were validated by comparing results from the three models to each other and then to results from an independent program (Design Pro-G v5.0); the results agreed to within 5%. By carefully evaluating results against engineering expectations, the effects of coupling PV models to shading and surface heat transfer models were verified (Griffith & Ellis, 2004). However, Energy Plus has some limitations as it does not include models for inverters, charge controllers or batteries. Also the modules are assumed to be always operating at the maximum power point. Similarly, the operating of the entire electrical system is assumed to operate in ideal ways. Therefore, the Energy Plus PV modelling and computing could be considered a method of predicting the upper end of electricity production rather than accurate values of what the modules would produce in a real installation(Al-Sharafi, 2011). In spite of this limitation, this research goal is to investigate the potentials of integrating the PV technology into the buildings and not to seek ultimate accuracy, especially when the PV market worldwide is continuously evolving new products with higher efficiency and different characteristics that could change any predicted electrical produced value. Moreover, this PV modelling computation in Energy Plus had been proved suitable in many published studies (Al-Sharafi, 2011)(Ordenes, Marinoski, Braun, & Rüther, 2007)(Wang, Esram, Martinez, & McCulley, 2009).

4.1 Typical Saudi Housing Unit (Base-case)

Saudi housing units vary in size and shape. In a study supported by the King Abdul Aziz Centre for Science and Technology (KACST) and conducted to estimate the demand for Saudi housing, results found that the average area of a Saudi villa is 592.3 m²and the average area per Saudi resident is 73.9 m²(El-deep, El-Zafarany, & Sheriff, 2012), the researchers estimated the area of a Saudi typical two-storey villa to be 256 m2 per floor, since the usual plot area is 500 m² and it is usually regulated as a maximum allowable built area of 60% of the land area.

For the current study, the characteristics of a typical housing unit were needed to establish a reference base-case as an important simulation component. The chosen unit was described in an interim report on a KACST Project and had been used by Ahmed in his energy simulation study of a typical Saudi house (Ahmad, 2004). As illustrated in the drawings in Figure 3, it has a rectangular plan shape composed of two storeys; each has an area of 262.5 m2 and height of 3.5 m. The characteristics of building, operating conditions (occupancy, lighting, air-conditioning and equipment) and air conditioning system, are given Ahmad (Ahmad, 2004). Furthermore, the specifications of construction materials were adopted from an earlier study (Taleb & Sharples, 2011).

4.1.2 Climate and Weather Data of Riyadh

Located between latitudes 24º and 28º N and longitudes 44º and 48º E, the arid desert climate of Riyadh city (or Arriyadh) is marked by extreme temperatures: very hot in summer and cold in winter, and great variation between night and day. In summer, the lowest average temperature ranges from 22–27ºC and the highest from 40–43ºC; while
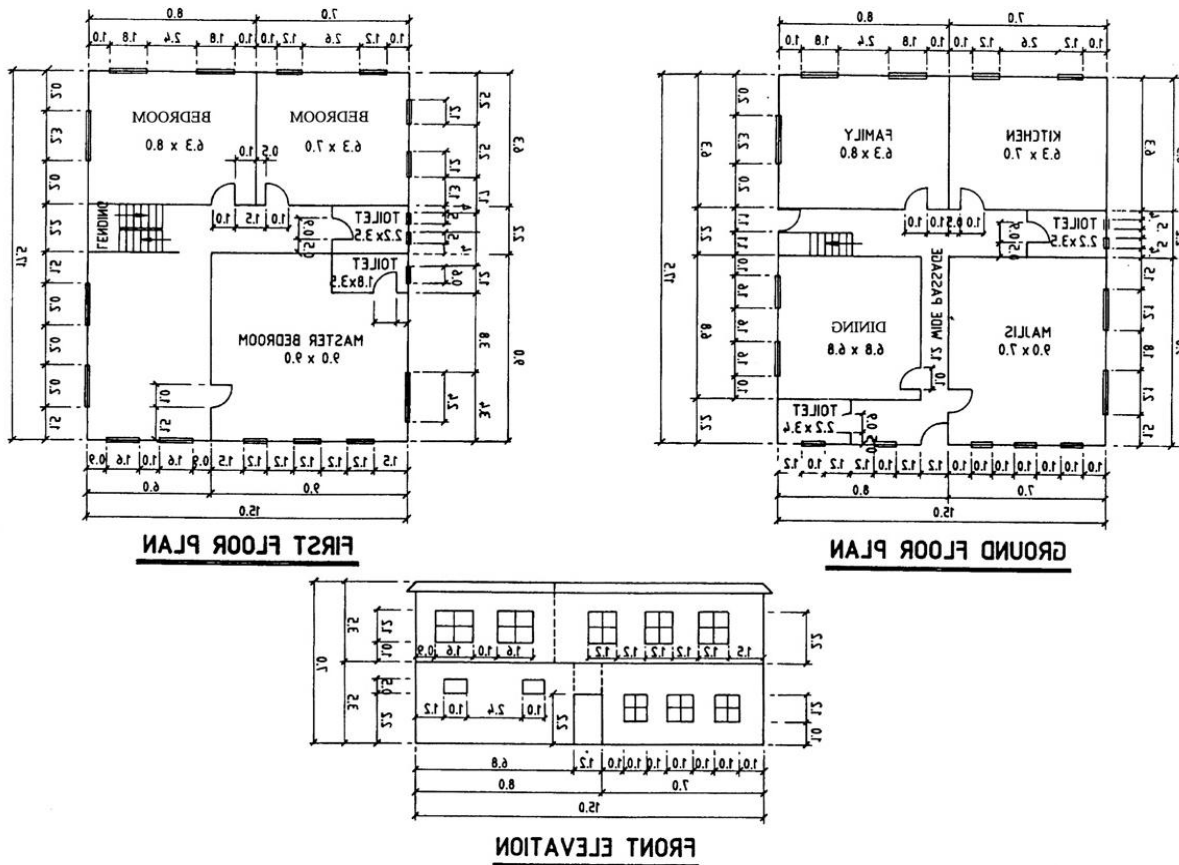

Figure 3: Typical Saudi house (Ahmad, 2004)in winter, the lowest temperature ranges from 8–14ºC and the highest ranges from 20–28ºC. Rainfall ranges from 10 cm to 13.1 cm (approximately four inches).

The humidity is generally low throughout the year, particularly in the summer season when it ranges from 10% to 13%. It increases in winter to reach 40% to 49% .

4.1.3 BIPV System Integration

The chosen BIPV ("Product Catalogue: ABA P6-54," n.d.) (Figure 6) has a considerable high power of 165Wp at NOCT1 conditions (225Wp at STC2); detailed specifications are listed in Table 1. In order to keep the production capacity fixed in all of parts of the study, the same module was used in all of them to make the comparison of results more accurate.

Each PV module consists of 54 solar cells aligned in fixed dimensions. As illustrated in Figure 4.9, the number of modules used in each investigation was in accordance with the need to integrate placement methods in multiples of 10, where each set of 10 modules forms a series.

Table1 : Specifications of ABA P6-54 PV panels ("Product Catalogue: ABA P6-54," n.d.).

| Specification	Description
Product name	ABA P6-54
Type of solar cells	156 × 156 mm polycrystalline
Solar cell efficiency	15.3%
Solar cells in module	6 × 9 = 45 cells
	1470 × 998 mm = Active area of 1.467 m²
Module weight	17.5 kg
Power of each PV module	165 Wp
Open circuit voltage	32.10 V
Short circuit current	7.26 A
Maximum power voltage	24.52 V
Maximum power current	7.71 A
Temperature coefficient of open circuit voltage	- 0.109 V/K
Temperature coefficient of short circuit current	0.00435 A/K
Operating temperature	- 40 to + 85°C
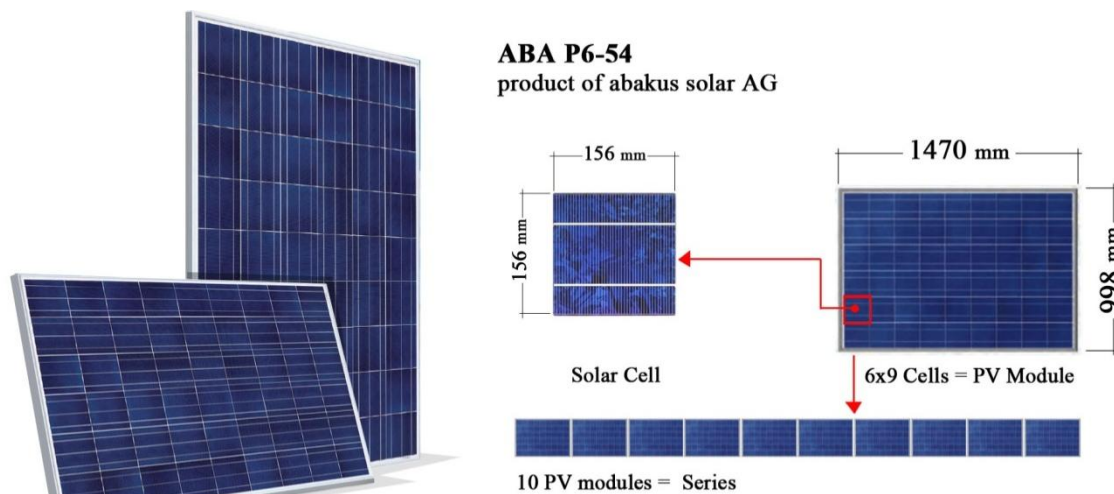
Figure6: BIPV type and elements

4.2 Base-case Modelling and Validation

At first the base-case model was created, then its energy performance was validated. Ensuring the study credibility was essential because all the other models, yet to come, were designed depending on its results and compared to it. Three outcome amounts were of interest and had been validated: electrical consumption, energy generation and GHG. Moreover, this part measured the received solar radiation on the housing unit's exposed surfaces, as a guide to identify the surfaces with the highest potentials to integrate the BIPV array.

4.2.1 Base-case Energy Consumption and CO2 Emissions

The typical Saudi house was identified here as the base-case, with all forthcoming cases compared to its energy performance. Its characteristics were modelled then simulated as it would stand solo on site with no surroundings that might affect the building performance. Since the house has a rectangular layout (W/L = 1.1), finding the best orientation for its long axis (17.5m) was needed for better energy conservation. When it was oriented east–west it consumed 9.4% more energy than if oriented north–south where all energy was consumed by cooling loads; thus the latter was used here as the study base-case orientation (Figure 7).
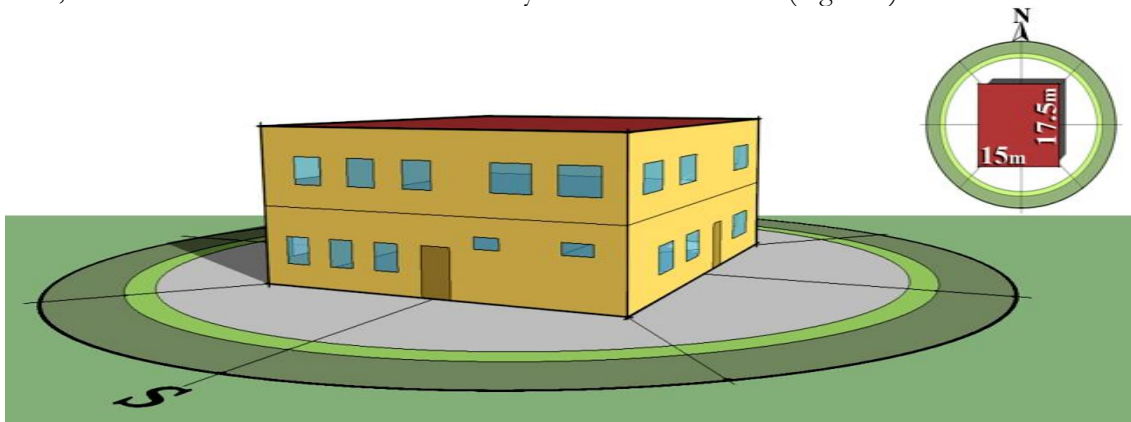
Figure 7 : Orientation of typical Saudi house model / Base-case

Simulation results showed 74,388 kWh of electricity is consumed annually, which equals 141.69 kWh/m2. The cooling load demands the highest share, constituting 78% of energy usage. Then comes the 13% and 8% share of interior lighting and interior equipment, respectively, while heating has the lowest share as it consumes less than1% (Figure 8).
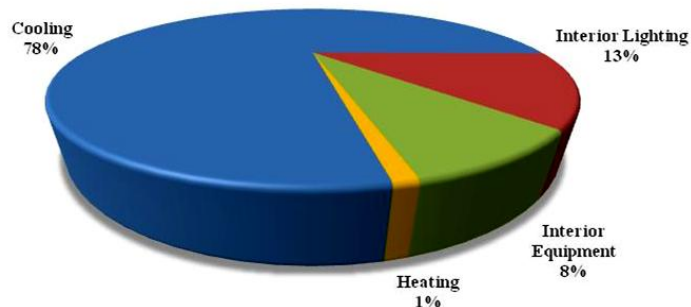

Figure8 : Base-case energy consumption

The carbon equivalent for CO_2 is calculated as an indicator to estimate the global warming potential (GWP) of the base-case. Considering electricity as the only used fuel here, the CO_2 emission factor for electricity usage in the Saudi household is assumed to be 0.757 kg of CO_2 per kWh (Enerdata, 2014). According to that, the estimated production amount for the base case was around 29.4 tons of carbon equivalent annually. As graphically illustrated in Figure 10, the electrical consumption increases in summer due to the increasing load for cooling where it reaches the highest produced level about 3592 kg in August, while in the cold days of December that amount decreases to 1,500 kg.

1.2.2 Electricity Consumption Validation

It was difficult to validate the simulation results where no standard value was found for the electrical amount a single Saudi villa can annually consume per m2. Furthermore, the energy performance of housing units is affected by many factors which make each unit act differently. Almaziad [49] confirmed that through undertaking a local field survey in Dammam city. He investigated and analysed the influence of residents' characteristics on energy consumption for residential buildings, and found that villas' energy consumption significantly
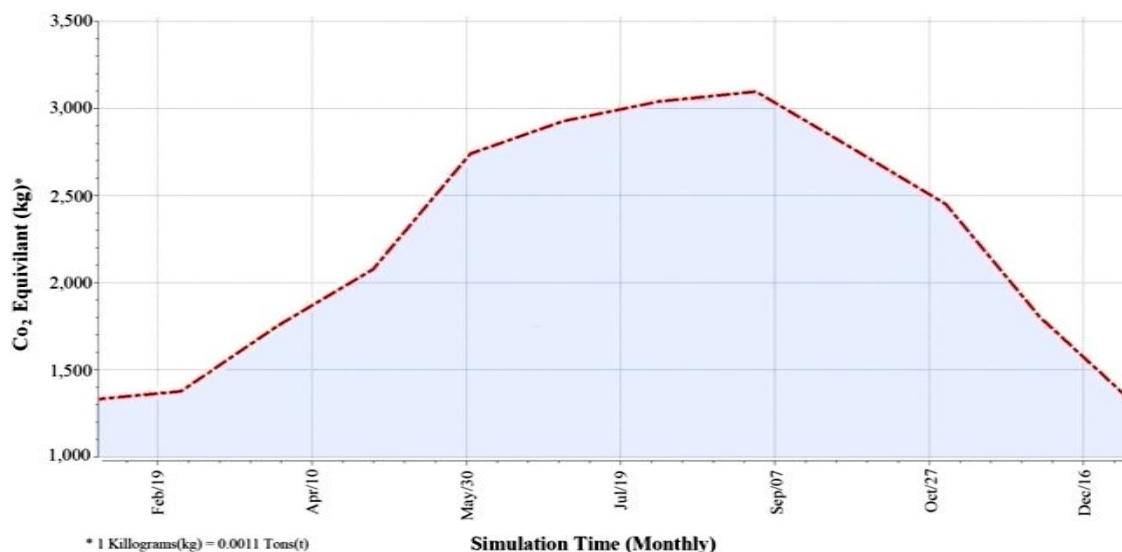

* 1 Killograms(kg) = 0.0011 Tons(t)

Figure 9: Base-case monthly produced amount of the carbon equivalent of CO2varied as the effects of factors varied from one to another.

The external or socio-economic factors such as house size, income, number of users, etc., were revealed to be most effective, along with buildings' physical factors such as exterior envelope insulation, shading, equipment, etc. However, results importantly showed that a villa could consume about 8,364 kWh in the hottest summer month (Almaziad, 2012). Close to that value are findings by Aldossary in his study of domestic energy consumption patterns in Riyadh city, where he found that a villa of 418 m2 could consume 9100 kWh while one of 699m2 could exceed 10,400 kWh in the hottest summer month, with 163 kWh/m2 as the annual average of consumption (Aldossary, Rezgui, & Kwan, 2014). Similar are the current study simulation results of the typical house as it consumes about 9,300 kWh in the month of August alone, which is a reasonable amount if compared to the above findings. Meanwhile, the annual consumption amount per area is around 141 kWh/m2, which is also a very sensible result as the used building envelope is insulated. The addition of thermal insulation has already proved to have a significant improving effect on the energy performance of Saudi residential buildings. Comparing that to the original study, Ahmed simulated the typical house unit in Dhahran, built with different materials than those used here (Ahmad, 2004).

In his study the effect of insulation on consumption is huge, around 42% where the unit with insulation consumes 153 kWh/m²compared with 263 kWh/m²without. Al-Ghamdi's study as well proved the benefit of roof and wall insulation, showing that in Dhahran city a house could annually consume 144 kWh/m2 of electricity (S. G. Al-ghamdi & Al-feridah, 2011). Also, Al-Saadi studied how the envelope's characteristics and design influences the energy consumption of residential buildings located in two cities with hot climates: in the study located in Riyadh he examined the differences and found that consumption could be reduced from 169 kWh/m²to 115 kWh/m2 (Al-saadi & Budaiwi, 2007). Moreover, Al-Mofeez found the consumption annual average could be 143 kWh/m²in Dhahran city with the consideration of energy conservation measures (Al-Mofeez, 2007).

4.2.3 Electricity Generation (BIPV) Validation

The amount of electricity generated by a PV system may vary depending on many variable factors such as site location, weather or the PV system specifications which in turn are very sensitive to change.

Other variables include the system modules' integration method, placement, tilt angle, etc. Any change in one of those mentioned factors or many others would certainly affect the energy generation potential. Therefore, it is hard to accurately validate the current study using the PV system unless it is tested in real controlled experiments, but that was not conducted here. In order to test the credibility of the results and to make sure that simulation results were within a reasonable range, data from the already-installed 5.28 kW capacity isolated grid PV power plant at King Fahd University of Petroleum and Minerals (KFUPM) (Rehman & El-Amin, 2012) was simulated in Energy Plus, then the two were compared. Their PV system was modelled and simulated in the same conditions as provided in their study as far as possible (Figure 10). The weather data for the same location in Dhahran city was used, also the same solar cell type, power, number and specifications were imitated as much as possible. Results showed a 20% difference in energy generation between the real and simulated models; that could be attributed to many reasons, some of which could be related to the accuracy of inputted data and some to the way in which the software processed inputs. In fact, Energy Plus does not predict accurate PV generated energy amounts compared to models of real installations but it does estimate the upper end amounts. It simulates the models in ideal environment conditions; for instance it does not calculate the possibility of accumulated dust on the modules' surfaces and how that might impact on the solar cell efficiency. Also it assumes that the whole electrical system operates in ideal ways; the inputs do not include some of the electrical specifications like the inverter model, charge controllers, power-point trackers, etc. (Griffith & Ellis, 2004). However, that difference was kept in mind while viewing the results of all investigations.

Figure10: View of: (a) the PV arrays installed at KFUPM beach, (b) PV control system installed inside the control room (Rehman & El-Amin, 2012).

4.2.4 Solar Energy Potentials of Buildings' Exposed Envelope

In studies of solar energy and buildings, the sun's position is a major factor that affects the building's energy performance in terms of both production and consumption levels. The knowledge of the annual sun-path of a specific building location is essential to make decisions and design the integrated solar energy system with regard to its placement, orientation and size.

It is also important for estimating the energy intended to operate the building which mainly depends on the received amount of solar incident by surfaces. The building's envelope represents the linkage between the external and internal environments. Having huge exposed surfaces with unobstructed access to sun radiation, that exterior envelope has the potential to integrate the PV system and so follow the sustainability approach. This study attempted to utilize all of the building's envelope surfaces (roof, exterior walls and attached components) except for the openings; neither fenestration nor doors were used. Influenced by diverse parameters, each examined surface was annually simulated and its potential was discussed through peak times in summer and winter (Figure 11).
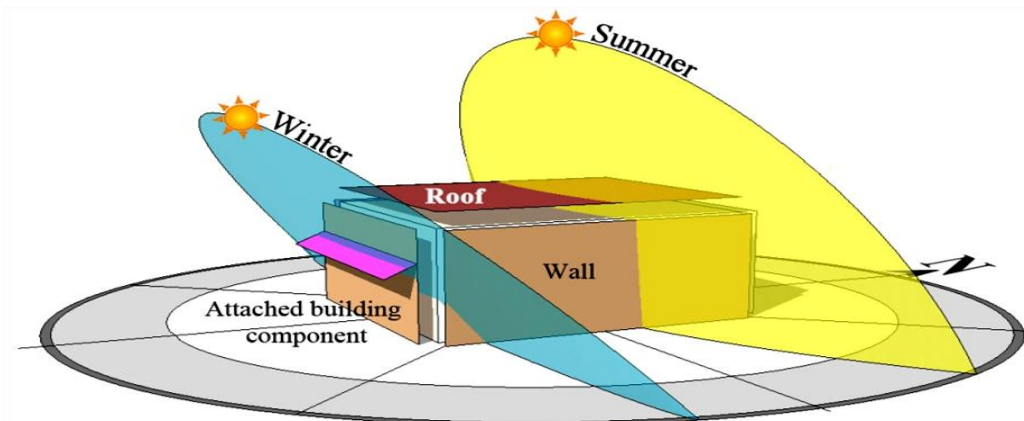
Figure 11: Building's envelope exposure to sun in summer and winter

4.2.5 Solar Energy Potentials of the Base-case Exposed Envelope

In general, after measuring the solar incident received amount by each of the base-case exposed surfaces, the roof was found the best surface to receive solar radiation, even though the exterior south wall receives it better for about a month in winter when the sun is low in the sky (Table 2). In summertime, the roof can receive more than 1060 W/m2 during peak hours at noon. During the same period the south wall does not receive much by comparison, and because of the high sun position, it even receives less than the north wall which has much lower solar potential almost all the year when compared with all of the other surfaces exposed to the sun. In spite of this, the south wall in winter can receive around 815 W/m2 during peak hours around noon. This antithesis between the roof and south wall is dramatically apparent in Figure 12. On the other hand, both east and west walls almost have the same solar potential, which reaches its highest in summertime and constantly becomes lower in winter

Table 2: Solar incident daily averages on the base-case exposed envelope surfaces

Surface	Roof	South wall	West wall	North wall	East wall
Solar Incident W/m²	253.7	143.82	133.08	59.92	130.91

According to the above analysis, the roof could have the highest potential for adding a BIPV array and producing high energy annually. Far behind comes the south wall with a large difference, almost half the amount. As for the other surfaces, the north wall has very poor potential because of the lack of direct solar radiation on its surface all year round. The east and west walls have good potential but only for limited hours as each receives solar incident for half the day.

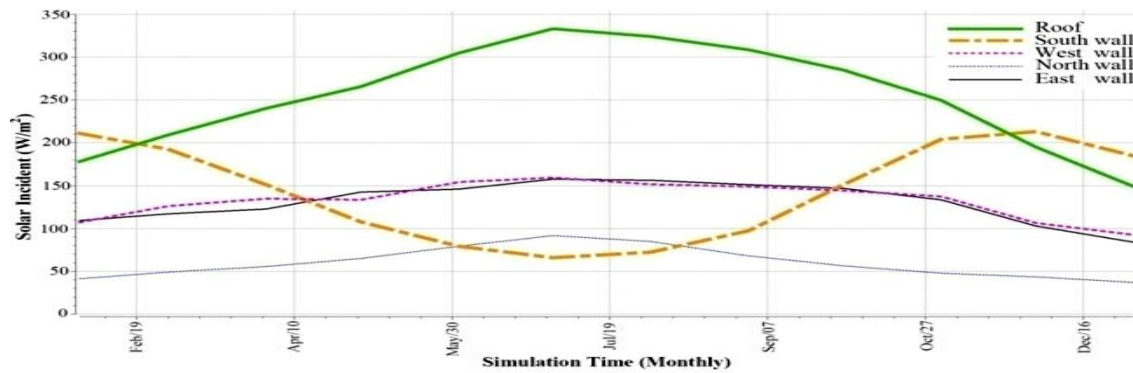### 4.3 Part Three: BIPV Potentials of the Solo Unit

Figure 12: Monthly solar incident on the base-case exposed envelope surfaces

From the previous part the received amount of solar incident on the base-case's surfaces was measured. Here, and according to that, the BIPV was basically added to the surfaces with the highest potentials; and depending on the methods the BIPV array is commonly integrated into the building's sun-exposed surfaces: roof, exterior walls (façades) and attached components. In each case the system integration was into a solo housing unit with no surrounding obstructions on site, so its actual full potential for energy generating could be measured. According to certain parameters each case had been diversified and tested. All the results of energy performance, either generated or consumed, were discussed through comparison to the base-case, where any change in consumption was identified and the produced energy's ability to cover the demand load was analysed.

4.3.1 Integration onto Roof Surface

As stated previously, the roof surface was found to be the best receiver for direct solar radiation, thus it has the highest potential to produce energy. Generally the roofs of buildings receive abundant daily amounts of direct solar incident being usually unobstructed; and in many cases they are unutilized which gives them great potential to integrate the BIPV to their surfaces. Roofs come in different types and forms, but this study addresses only two: **flat** and **tilted**. The flat roof type is locally typical and commonly used in the Saudi residential building industry. By comparison, the tilted roof type is not that popular locally, it has no specific common shape or angle and is mostly used for aesthetic purposes. However, the latter type was studied here, based on the rule of thumb which indicates the prefer ability for buildings located in the northern hemisphere to integrate south-oriented BIPV arrays with a tilt angle equal to the latitude of their geographical location. According to that, two parameters were investigated: the tilt angle and the orientation of roof surfaces, thus the integrated PV modules as depicted in Figure 13. Five tilt angles were tested; the main one is a tilt angle equal to Riyadh's latitude, 24.7°. That angle was twice increased by 2° and then twice decreased by 2°, in order to find out if the angle equal to latitude has the highest potential for producing energy all year. It should be noted that, while designing the added BIPV array on the roof surface, the area needed for the system and the number of PV modules were calculated after considering leaving an empty area of 40–50% of the total roof area for any other use by the house users or for any electrical appliances that might be used to operate the house. Accordingly 80 PV modules (8 series) were suggested and tested in the both investigated roof cases: the flat and tilted types.

4.3.1.1 BIPV on Flat Roof

At first, the BIPV was integrated on top of the base-case flat roof, acting as a building sustainable construction material that produces energy (Figure 14). Simulating the model showed that 80 PV panels (8 series) of the proposed BIPV system, at best conditions, could produce 42% of the housing unit's total energy load if compared to base-case electrical demand.
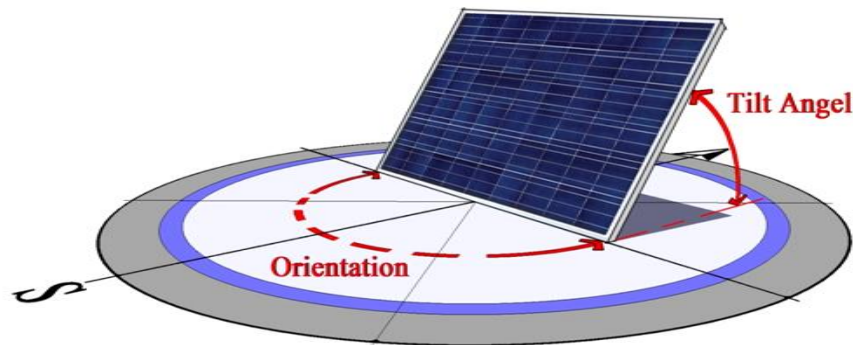
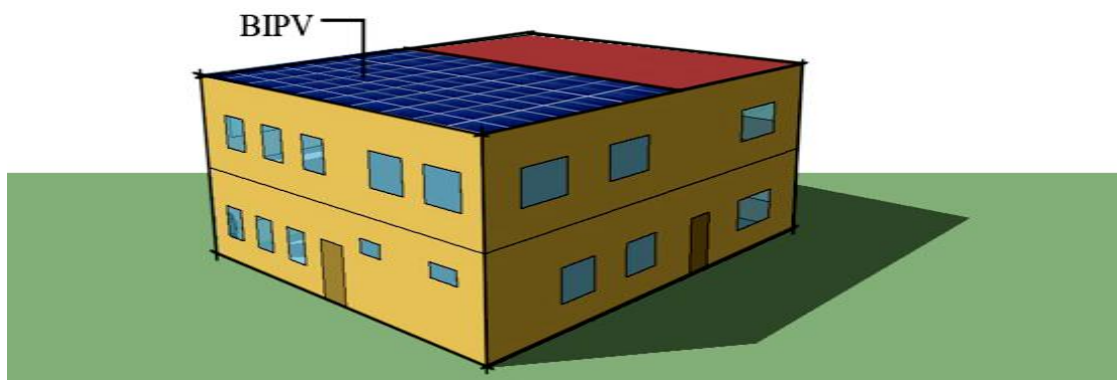**Figure13: The two parameters studied for adding the BIPV array on tilted roof**

Figure 14: BIPV on the housing unit flat roof

However, there was one minor drawback caused by the direct integration of the PV modules on the roof surface. When the electricity is generated the solar cells heat up; consequently the cells' produced heat was transmitted through the roof's construction layers to the internal environment of the housing unit, forming by that a new source of heat gain. That increased the internal temperature, thus the cooling load was increased. In total, the electricity consumption was increased by 2% which meant that the generated 30,406 kWh of BIPV electricity could cover about 40% of the housing unit's annual energy demand. Moreover, the cells' increased heat lowers their efficiency; and as any semiconductor they are negatively affected by that due to increased resistance.

The hot solar beams plus the high ambient temperature both overheat the surfaces of solar cells which impacts on their production of electricity. By being sensitive to temperature, the used solar cell might lose about 0.5 % of its efficiency for every 1°C increase in the cell's temperature above the standard conditions. The relationship of the temperature increment and the cells' efficiency is illustrated in Figure 15: even though the amount of solar incident on the roof surface is higher in the summer months (which implies great potentials as discussed earlier), the very hot temperature negatively influences the energy performance of the integrated PV cells. In such instances, using photovoltaic thermal hybrid solar collectors (BIPV/T systems) might produce the energy without the mentioned problem, where the produced heat could be utilized either in water heating or internal air heating on cold days. However, that issue was not addressed in this study.

4.3.1.2 BIPV on Tilted Roof

The previous roof form would be suitable for the summer season as the solar beams are perpendicular on the flat roof surface at noon hours owing to the building's geographic location. Yet that is not the maximum potential for the solar cells integrated; according to the literature the fixed BIPV modules should be tilted to the

same degree as the geographical latitude to improve its performance and to have a better chance of capturing solar radiation in all seasons. In this case the used roof here had been tilted to the angle of 24.7°, which equals the latitude of the housing unit in Riyadh city and then the BIPV array was added, as illustrated in Figure 16. That kind of adjustment would change the building's architectural design; it even might change its volume either by increasing or decreasing it
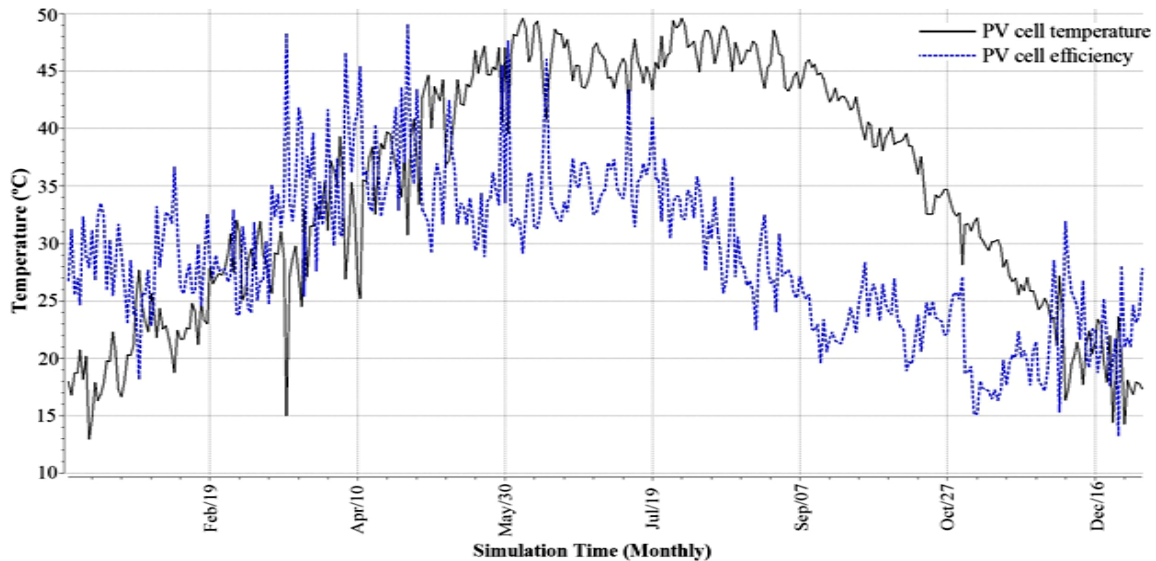

Figure 15: Relationship between temperature increment and cells' efficiency

Actually it is up to the architect and the design team as to how they would design the roof form: if they could introduce the BIPV system at the early stages of project designing, then for better living and better sustainable architecture could result, like the examples previously viewed in the literature chapter. Figure 17 shows some of probable roof forms. To keep the change to the minimum in this study, only one part of the roof that could contain 80 PV modules (8 series) had been tilted, which on the other hand created 207.85 m3 of increased internal volume to the upper floor. Measuring the impact of that change on the energy consumption amount was crucial. It was found that even though the volume increased, yet the consumption decreased by more than 3% due to the self shading created by the roof's tilted part. So the shading here had a more effective impact on energy consumption than that change in the internal volume.
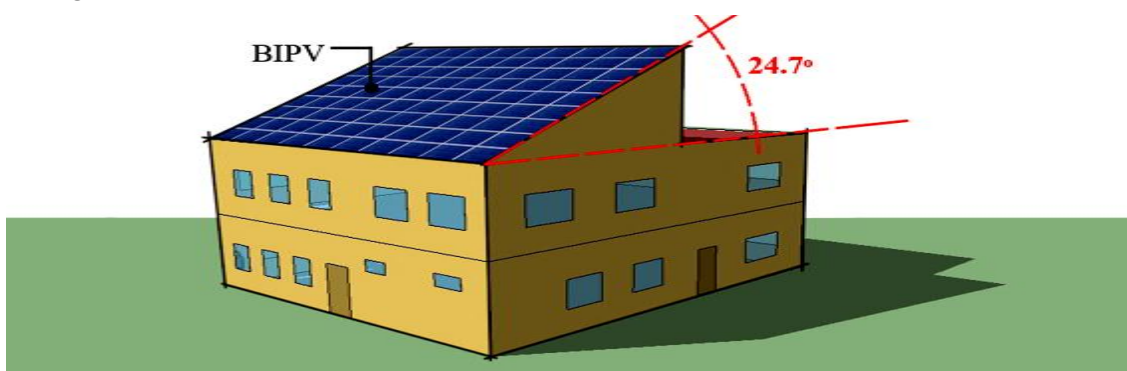

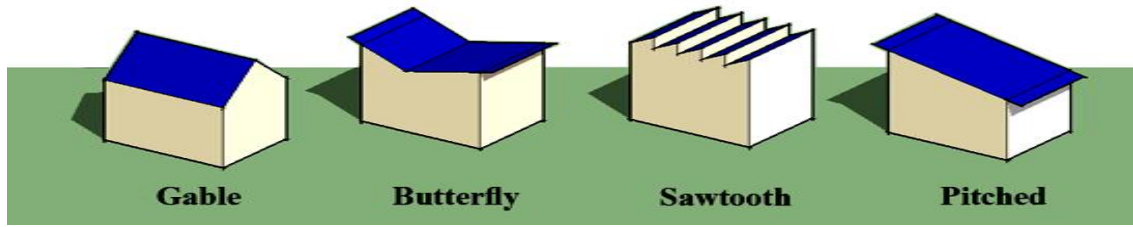**Figure 16: BIPV on housing unit tilted roof**

Figure 17: Some probable roof forms for integration of BIPV

The tilt angle of the roof increased the BIPV energy production by 4.7% if compared to flat roof's electricity generation amounts; the daily average of received solar incident on the tilted roof was found to be more than that received by the flat roof (Table 3), as the former in the peak hours could receive about 1105 W/m2. The annual generated energy could cover about 44% of the electrical load demand that already had been reduced due to the self-shading explained earlier. The monthly differences in energy production between the two roof forms is illustrated in Figure 18; although the potentials of the flat roof is higher in summertime, the tilted roof is better overall.

Table 3: Solar incident daily average of the two roof forms

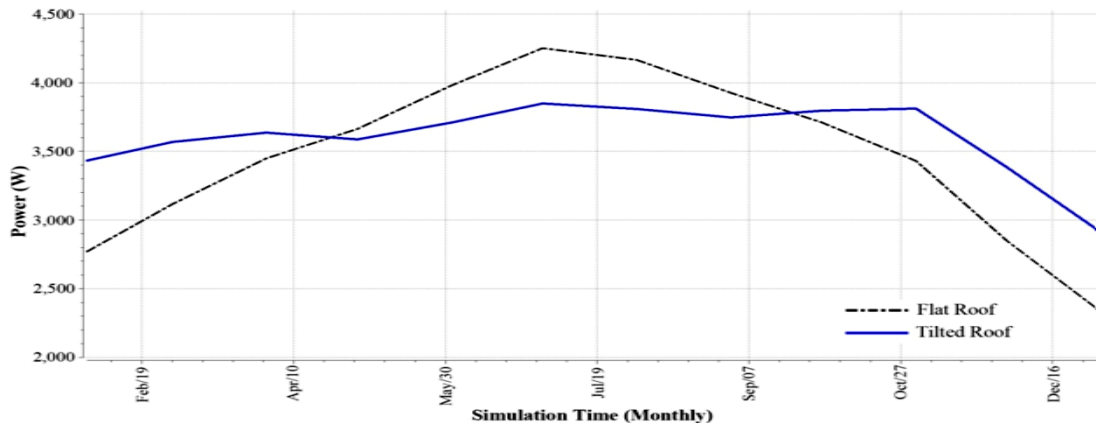| Roof form	Flat	Tilted
Solar Incident W/m²	253.7	272.89

Figure 18: Differences in the potentials of energy performance for the two roof forms

Two increases and decreases by 2º in the tilt angle were also examined to find if the latitude tilt angle provided the highest potential for harvesting more solar radiation. With a difference of less than 0.5% between the five tested angles, that variance of angle tilting was considered insignificant; although increasing the angle's tilt reduced the BIPV potential three times more than decreasing it. For each tilt angle, as much as the BIPV energy generation amount becomes more in summer, in winter it becomes less, except around the period of the autumn and spring equinoxes, where the potentials are equal for all the tested BIPV tilt angles (Figure 19). To have the best tilt angle and orientation for each season, sun trackers could be added but that was not discussed in this research.
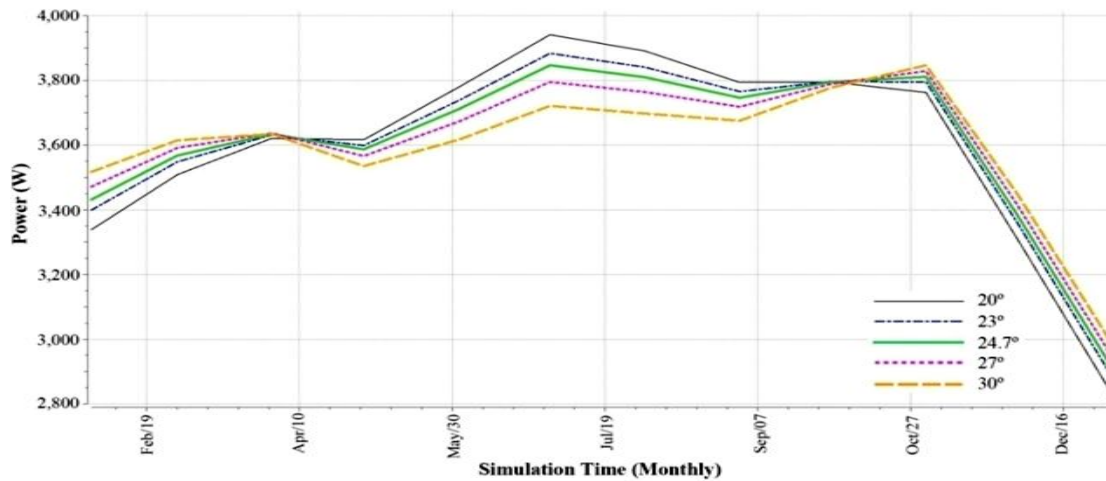
Figure 19: Differences in the potentials of energy performance between the tilt angles

4.3.2 Integration onto Exterior Wall (Façade)

Façades usually form the largest area of any building's sun-exposed envelope. In order to exploit that huge area, their solar energy potential was examined in this study. The base-case unit has a wall gross area of 455m2 with 11.8% window to wall ratio (WWR): each wall area and its openings percentage are listed in Table 4. The openings percentage and their location were kept fixed; that was very important for every wall to have more accurate readings for electricity consumption and to measure the impact of the other parameters clearly. It should be noted that solar energy potential for all openings was excluded in this study; otherwise the investigating would then have needed a special kind of BIPV and not the type used in this study on all the other building surfaces. Certainly it would affect one of the investigation goals to compare the surfaces' potential to each other, when changing this primary parameter.

Table 4: Area, dimensions and percentages for all the housing unit's exterior wall surfaces

Exterior wall	Gross	North (315 to 45 deg)	East (45 to 135 deg)	South (135 to 225 deg)	West (225 to 315 deg)
Wall area (m²)	455	105	122.5	105	122.5
Window area (m²)	53.49	14.4	14.2	12.8	12.1
WWR (%)	11.8	13.7	11.6	12.2	9.9
Doors	5.1	-	2.4	2.6	-

The housing unit walls were divided into segments to find the best placement for BIPV; while bearing in mind the openings locations and the PV modules dimensions, as illustrated in Figure 20. All windows are 1.2 metres high except for those of the bathrooms, which are smaller. This means that each wall is divided into six segments like ribbons, in accordance with the BIPV modules dimension (one series) and then they are integrated on the unit's walls (above, below and between their openings). The solar energy potential was investigated for each segment, to find if there was any difference in receiving the solar radiations, thus in the potential for generating energy. The orientation of all simulated models in this case was fixed to true south like the base case. Then, each of them was simulated in the solo unit model with no surrounding obstructions, although this is rarely the case in reality. Sometimes there are obstructions that might block sun radiation.
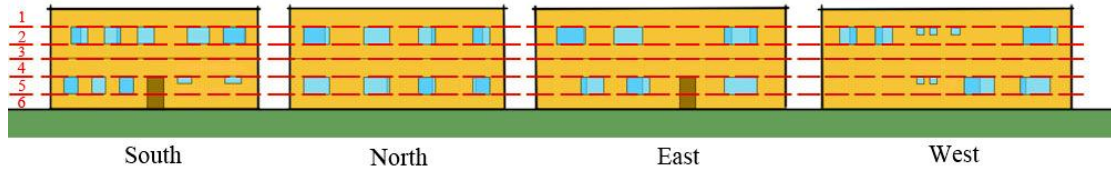
Figure 20: Building's exterior walls divided into six ribbon-style segments

4.3.2.1 BIPV on Exterior Walls

This case was investigated through many simulated models, to measure the BIPV energy generating potentials within each segment individually. It showed that the integration of BIPV on segment #1 had the best potentials, even though the difference is minor between each segment and the ones below it. The total generating difference between #1 and #6 is only 1%, as it decreases downwards. With this insignificant difference, the BIPV could be placed at any segment of the same wall with no noticeable effect on its electrical generation potentials. Of course that is the case only if no obstructions exist that would prevent the solar cells receiving direct sun radiation (Figure 21). On the other hand, the integration location of the BIPV modules on certain exterior walls is very significant if there are any obstructions that could cast shading; the latter would ruin the BIPV energy production potential.

The obstructions come in many forms, as, say, neighboring housing units, or components attached to the building itself (Figure 22). Generally, in both forms the top area (segment #1) of the housing unit's exterior wall is usually unobstructed and has the highest potential to receive solar radiations, thus producing energy. The generated energy of one BIPV series installed on the wall top area (segment #1) of the south wall is lower by 40% than the same one installed on the roof. However, its energy generation potential is 10% better if compared to the west wall or east wall.
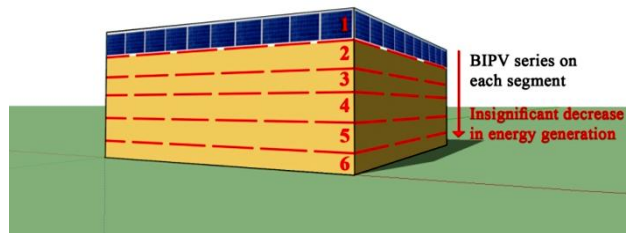

Figure 21: Insignificant difference in locating BIPV on certain wall due to absence of obstructions
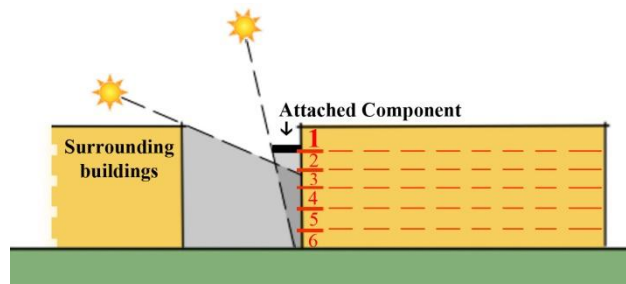

Figure 22: Significant difference in locating BIPV on certain wall due to obstructions

On the other hand, the west wall has more potential than the east wall, although the difference is very little (about 0.5%). It should be noted that the north wall energy generation potential was not examined here as early simulation results showed it has very low solar potential, so it was excluded. All of the discussed indications firmly indicate the top area of the south wall as the preferable placement location to integrate the BIPV on the housing unit's exterior walls, where it usually has full sun exposure.

With one BIPV series, as illustrated in Figure 23, the amount of 2,380 kWh of electrical energy could be produced annually, which would cover about 3.2% of the total consumed electrical load.
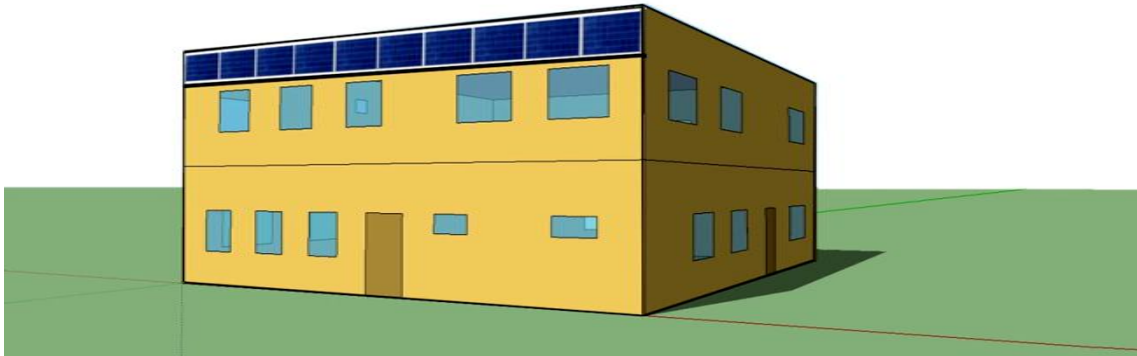

Figure 23: BIPV placement for maximum performance on south wal

4.3.3 BIPV as an Attached Building Component

There are many kinds of components attached to buildings, and these may be added for functional or aesthetical purposes. This study focused on the shading device component; known for many centuries, it is widely used in architecture as a way to adapt to nature, and it is also known for its great potential in conserving energy.

Moreover, the study added the shading device to the base-case model and then utilized its surface as BIPV, especially because the addition of this component type would not involve changes to housing unit planning, and it was already proven in a lot of studies to be a very suitable method of integrating the BIPV modules. This part of the investigation chose the shading device type and its dimensions according to the building's geographical location and to the sun's position.

4.3.3.1 Attached Component: The Shading Device

Similar to any other surface of a building's sun-exposed envelope, a window receives solar radiation in any of its different forms (direct, diffused and reflected). External shading devices can diminish that by eliminating the direct radiation, which is normally the largest source, while it can also reduce the diffused radiation (Szokolay, 1996).

Shading devices come in many different types and forms, but this study focused just on one: the **fixed horizontal overhang**. This type was chosen mainly because it is the most commonly used shading device for south-facing walls: both the earlier investigation findings of this research and the literature recommendations suggested that this addition would serve to conserve energy and would create great potential for energy generation if the PV system is integrated. It should be designed to control the solar heated season by shadowing the south-facing fenestration, thus blocking the high-angled summer sun, while allowing the low-angled winter sun an access to the internal spaces. Moreover, and especially for this case, the device design should be adequate to site the PV modules used in this research. Thus its placement was limited to shade the first-floor fenestration, as the shadows either created by the shading-device itself or by the surroundings would ruin any chance of adding further BIPV modules below that chosen level. The **shading device size** was designed by reference to Szokolay's method (Szokolay, 1996).

4.3.3.2 Design Parameters of the Shading Device and the BIPV

Designing the shading device placement and its dimensions depended on four parameters, though also bearing in mind the already-specified 50° VSA. Three of these parameters were kept stable, while only one was varied: the tilt angle. This was in order to measure the latter's changing impact on the amount of received solar incident on the BIPV surface. All used parameters are described below and illustrated in Figure24:

¬*Window height (H):* all the included windows have the same height of 1.2 metres.
¬*The gap (G):* represents the distance between the top of a window and the device's underside surface. It is an important parameter, and manipulating its distance could change the device's dimensions for a certain VSA.

Therefore here it was considered as having a fixed value of 40 cm above windows, with the purpose of reaching more precise results related to the studied subject. It should be noted that it was not intended to be a limitation, but this value was chosen as an example to ensure having enough space to integrate the proposed (1m-width) BIPV module into the shading device surface, even when changing its tilt angle as described later. Also, that proposed Distance had the advantage in providing more window view, especially when the tilt angle was big.

¬*Shading device dimensions:* being a rectangular shape, the shading device depended on two dimensions, the width/projection (P) and the length (L), to define its shape and area. The former was not indicated here by a certain value but it was considered as the horizontal distance bounded by the gap's vertical end point above the window and by the already-specified VSA. That would allow the projection dimension the flexibility to change with each tilt angle. Meanwhile the length dimension was considered a fixed value; it was extended along the 15-metre length of the south wall. That would ensure shadows being cast on all the first-floor windows of that wall.

¬*Tilt angle (T):* five angles at 15° steps were tested (0°, 15°, 30°, 45°, 60°) plus that of the location's geographical latitude angle (24.7°); and all were south-oriented.
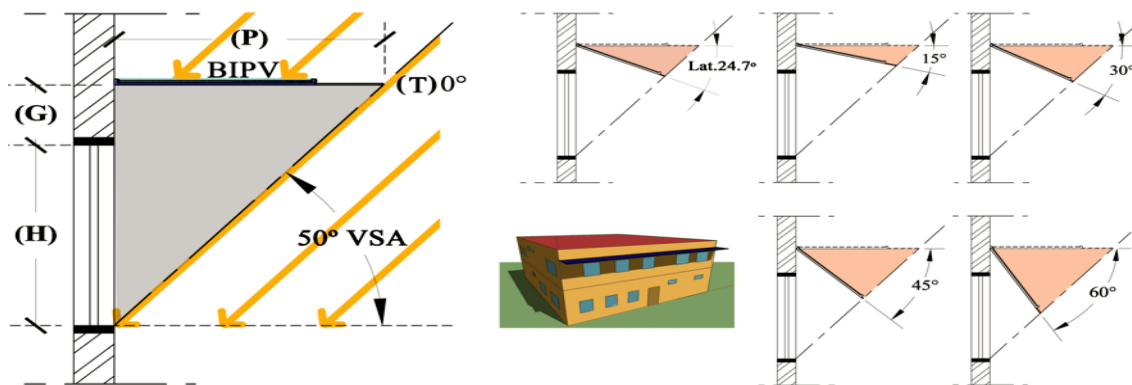

Figure 24: Design parameters for the BIPV as shading device

4.3.3.3 BIPV as Shading Device

The integration of 10 BIPV modules (1 series) into the designed shading device were examined for each proposed tilt angle. Their energy production potential was investigated, and results were compared to the consumption amount that could be covered. Also the consumed energy of the varied simulated models was compared to the base-case demanded load.

There are some parametric similarities between the BIPV applied on the roof and the ones proposed here as shading devices; they are both oriented towards the south and they match in some of the proposed tilt angles. Therefore the energy potential for them all was compared, and results were analysed accordingly.

Results showed that the 0° tilted BIPV produced 2% less energy as a shading device than its counterpart integrated into the flat roof. This small decrease was due to the building's self-shade casting on the solar cells, especially at sunrise and sunset. In contrast, the BIPV as a shading device produces 3.2% more energy than the ones on the tilted roof. This was not only because of the tilt angle value which made the solar cells' surfaces away from the building's self-shade range, but also because of the integration method. The BIPV as shading device allowed the solar cells to lose some of their builtup heat as there is no attached surface below them, thus their surfaces could cool down. In contrast, on the roof the solar cells are directly integrated to the roof surface. The increment and decrement in energy production for the 15°-step angles is oscillating within the range of 500 kWh annually, which equals 12% difference in production between the largest and smallest tilt angle value. The angle of 30° is the highest producer, while for the rest of the angles starting with 0°, the production increases as the angle's value is increased, until reaching 30° when it decreases constantly. Generally the angles smaller than 30° produce more energy than larger ones, even though the difference is minor.

The impact of tilt angles on the BIPV power generation is illustrated in

Figure 25; and it shows the small difference between 30º and 24.7º potentials. However, small angles perform better in summer and the opposite happens in winter. The illustrated proposed 30º tilted BIPV as shading device in Figure 26was found to produce 4,080 kWh of energy, which could cover about 5.7% of a consumption load already reduced by shading. Adding the shading device reduced the consumption by more than 4% compared to the base-case's amount, where the cooling load was the most affected (Figure 27). Even though the heating load increased about by 37%, that was not really effective as heating just consumes less than 1% of total load (Figure 28).
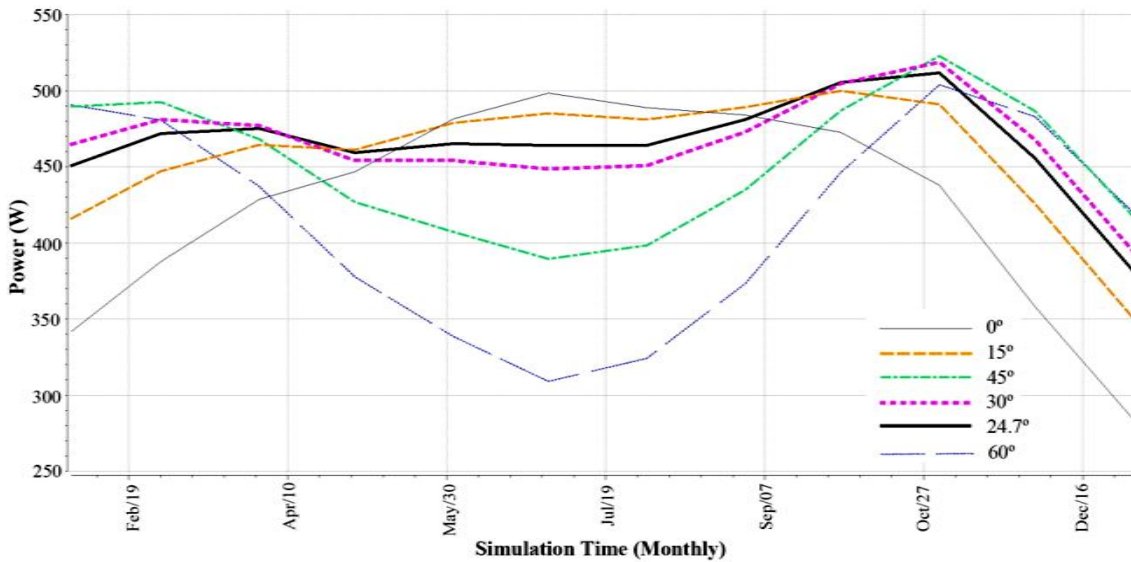

Figure 25: Impact of tilt angle on energy generation potentials of BIPV as shading device
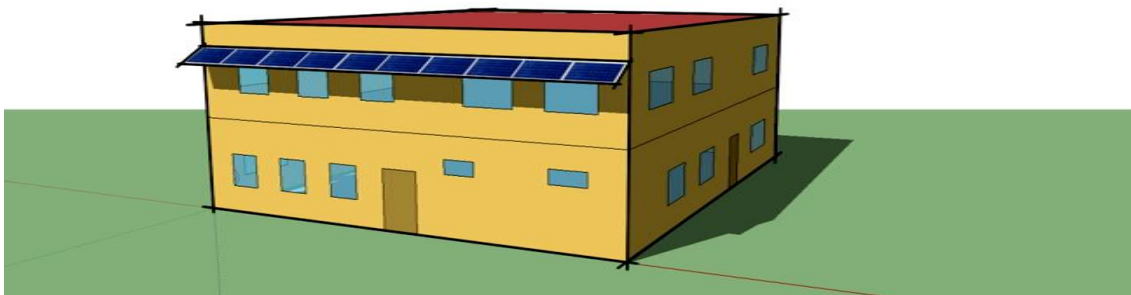

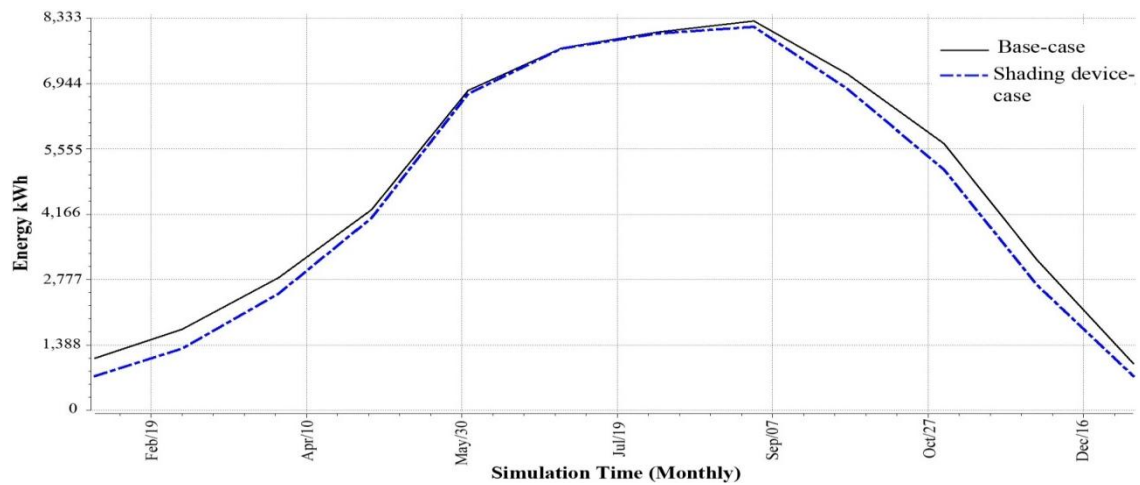**Figure 26: BIPV as the housing unit shading device**

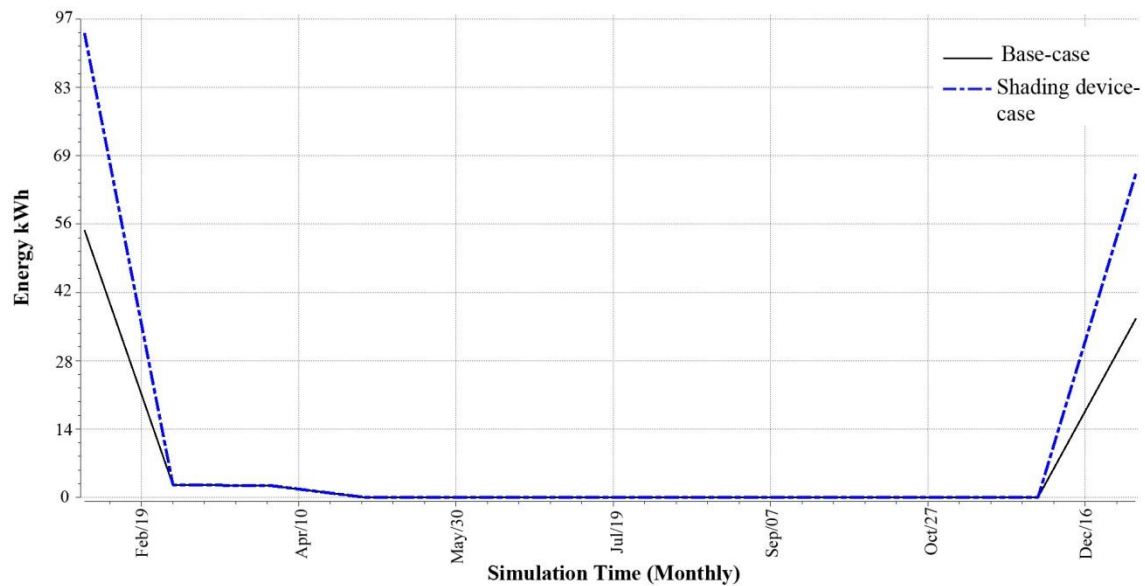**Figure 27: Change in cooling loads after adding the shading device**

Figure 28: Change in heating load after adding the shading device

5. Conclusion

This study aimed to investigate the potential of implementing BIPV systems in the Saudi residential sector, specifically the villa type of housing as it represents the sector's largest segment. Observe the impact of integration on the architecture of housing units; then to determine the influence of the addition of BIPV on the rates of energy generation and consumption on two levels, that of the country as a whole and that of the consumers; also, to measure the potential of solar energy in mitigating the effects of global warming.

Investigation of the study goals proceeded through simulation and based on the literature. Modelling the study cases needed some initial data as inputs for the Energy Plus engine. In the first part of the study, this data was collected from different resources as appropriate. Accordingly, in the second part, the typical Saudi house was identified as the base-case model, where all the investigated cases in this study were compared to its energy performance. Its characteristics were modelled, and then tested through simulation as a structure standing solo in its site with no surroundings that might affect the building's energy performance. Eventually, the findings of its energy consumption and generation were validated.

The building's long axis was oriented north–south for better energy conservation. It was found to consume 74388 kWh of electricity annually, which equals 141.69 kWh/m2. The task of cooling had the highest share, constituting 78% of the energy consumed.

The estimated annual production amount of CO_2 equivalent was around 29.4 tons. Moreover, the solar energy potential of the base-case was examined for nearly all its exterior surfaces; first, by measuring the amount of incident radiation for each surface, then by integrating the PV cells to each of them differentially. Of all surfaces, the roof was the highest recipient of solar incident, while the north-oriented wall was the least. On the other hand, the south-oriented wall had significant potential and was considered the best of walls to integrate the PV array as it received solar radiation almost all day. Whilst the east- and west-oriented walls were not that far behind in their potentials, each of them receives solar incident for only half the day due to sun position and building location. Accordingly, the study focused on integrating the PV array to the roof and south-oriented surfaces.

Estimating the buildings' solar energy potentials depended on multiple correlations of parameters and variables, which were determined and then tested through simulation to identify their impacts on the energy performance of the investigated modelled cases. On the other hand, a number of factors were found that could negatively impact these potentials and influence the PV cells' performance. However, the study only focused on the shading factor, due to its profound impact. That impact was studied here, as the buildings are usually subjected to shading from their surroundings or by their own shape (self-shading), which eventually would affect the BIPV energy generation.

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