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Integrating Solar Photovoltaics in Residential Buildings: Towards Zero Energy Buildings in Hail City, KSA

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Abstract: In recent years, most cities have faced great demand for electricity supply due to rapid population growth and industrialization. Supplying sufficient electrical energy, while reducing greenhouse gas emissions, is one of the major concerns of policymakers and scientists all over the world. In Saudi Arabia, local authorities are increasingly aware of the necessity of reducing the environmental impact of nonrenewable energy by exploring alternative sustainable energy sources and improving buildings' energy efficiency. Recently, building-integrated photovoltaic (BIPV) technology has been regarded as a promising technology for generating instantaneous sustainable energy for buildings. To achieve a substantial contribution regarding zero energy buildings, solar energy should be widely used in residential buildings within the urban context. This paper examines how to achieve an appropriate model for integrating photovoltaics on the rooftop of residential buildings in Hail city to provide alternative energy sources. The estimated rooftop areas in Hail city, utilizable for PV application were calculated. Using PV*SOL simulation software, the performance ratio and the system efficiency, as well as the annual energy output in several tilt angles, were determined and presented. The amount of energy expected when using all effective roof area in the city was also calculated. The amount of CO_2 emissions that could be reduced as a result of using a PV system was estimated. The results show a significant area of rooftop suitable for PV system in residential buildings in Hail city, which exceeds 9 million square meters. On the other hand, the performance ratio and the system efficiency are affected by the tilt angle of the PV module, where the efficiency increases with higher tilt angle, this is due to the PV module temperature, where, with the decrease in the PV module temperature its efficiency increases. The results indicate that the 30° tilt PV produced the highest amount of energy, whereas the 75° tilt PV records the smallest one although it achieves the best possible efficiency. There is a significant amount of energy produced from the use of all residential rooftops in Hail, and there is also a significant reduction in the amount of CO_2 emissions. It is expected that this research would develop innovative building design strategies and specifications allowing for better climate and energy efficiency as well.

Keywords: solar energy; residential buildings; rooftop; building integrated photovoltaic (BIPV); zero energy buildings

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1. Introduction

Around the globe, concerns are growing over conventional carbon-based energy production. Burning fossil fuels to generate electrical energy has been confirmed to be a major contributor to greenhouse gas emissions and can cause serious environmental and health problems [1]. Recent predictions indicate that electricity is the fastest growing final shape of energy with increased demand worldwide [2]. In the Kingdom of Saudi Arabia, the electricity demand has increased exponentially over the last two decades, and this is expected to continue increasing dramatically due to the rapid population growth coupled with great urbanization and industrialization [3]. According to the International Energy Agency [4], the Kingdom of Saudi Arabia will need vast energy resources in the coming decades for electricity generation, desalination, and process heat [5]. This enormous energy consumption has led to serious ecological, environmental, and public health problems caused by the effect of higher greenhouse gas emissions, primarily CO_2. As per the World Bank data, Saudi Arabia's total greenhouse gas emissions have tripled since 1990, accounting for almost three times of the G20 [6]. The residential sector is the largest energy consumer in Saudi Arabia with more than 53% of the total national energy, accounting for 296 billion kWh, and with an annual growth of 5–8% approximately [7]. It is reported that, compared to 2009, the power demand in the residential sector is expected to double by 2025 [8]. Domestic electricity consumption in Hail province is also bound to be propelled to unprecedented levels, causing power outages that are now so frequent during harsh summer temperatures when power demand peaks become an unwelcome mainstay.

With its huge oil reserves and proper planning, Saudi Arabia, in principle in the short-term, has no problem meeting the increase in energy demand using the current fossil-fuel-based production methods. However, decision-makers and the scientific community are increasingly accepting the fact that economic development based on nonrenewable resources is unsustainable in the long run. Therefore, there is an urgent need to look ahead and plan for the post-oil era by implementing innovative sustainable energy solutions. Renewable energy technologies provide an exceptional opportunity for mitigation of greenhouse gas emissions and reducing global warming by substituting conventional energy sources (fossil fuel-based). Solar energy is one of the most promising, reliable, and environmentally friendly renewable energy technologies. It has the potential to significantly reduce reliance on fossil fuels and decrease environmental impacts [9]. Interests in renewable energy are growing as people work to build a sustainable future where the electricity demand is met. Considering the plentiful solar radiance and the prevailing desert climate conditions in Saudi Arabia, photovoltaic (PV) technology could play a vital role to overcome energy issues in this hot and arid region [5]. As part of Vision 2030, the Saudi government has recently launched an ambitious solar project worth $108.9 billion and with a target of achieving 41 GW of solar capacity to supply one-third of building consumption by the year 2032 [10].

On the other hand, the movement towards transforming buildings from energy users to energy producers has not appeared at this moment. Architectural, structural, and aesthetic solutions to integrate PV into the building have been discussed since PV first appeared [11]. The concept of zero energy buildings is no longer perceived as a concept of a remote future but as a realistic solution for the reduction of energy use in the building sector [12]. One significant aspect of energy-efficient buildings is building-integrated photovoltaic systems that can contribute effectively to the amount of energy required for cooling and artificial lighting, as well as improve thermal and daylighting quality [13]. Photovoltaic-integrated systems are thoroughly compatible with the concept of zero energy buildings and sustainability criteria considering the advantages of reducing the number of materials and installation spaces needed, as well as lifetime costs. The use of PV systems can offer a cost-effective and aesthetically acceptable means for buildings [14].

Although photovoltaics have traditionally been more expensive than grid power, the cost of PV cells has declined drastically in recent years. However, in densely populated metropolitan areas, it is impractical to install large ground-based solar arrays. Therefore, urban PV systems must be integrated into buildings, which present an opportunity to pair energy supply with local energy demands. Building integrated photovoltaic (BIPV) systems have increasingly been incorporated into elements of recent building enclosure systems [5]. Building integration of photovoltaics can be executed on sloped roofs, flat roofs, facades, and solar shading systems. PV cells may be mounted above or on existing or traditional roofing or wall systems [15]. In other words, BIPV systems have a dual purpose: they serve as building envelopes and as on-site energy production at the same time [16].

Despite the high potential for BIPV applications, there is the need to overcome technical, social, and economic barriers to reach a larger scale of BIPV applications [16,17]. Based on the Arab environment in general and the Saudi environment in particular, it is clear that the unity of thought and belief is one of the most important factors that shaped the concept of building in the Islamic city, where customs, traditions, and privacy are the most important principles that have shaped the concept of housing and residential buildings, as well as the nature of the desert environment and the need for climate-appropriate design, cannot be overlooked. All of these reasons led to some external forms of the façades, which in turn led to the difficulty to use PV panels, such as increasing the depth of the levels to increase shade while reducing the area of the openings, which reduces the importance of using PV panels in windows as well [18–20].

Despite the economic development in Saudi society, the connection with the environment led to the association with traditional environmental materials such as stone, marble, or concrete blocks, which in turn led to the refusal of renewal or going towards modern technologies [20]. Solar PV performance depends on the local climatic conditions and availability of solar radiation [21], therefore, one of the problems facing the installation of photovoltaic panels on the facades in Saudi Arabia is the orientation towards the largest possible amount of solar radiation, where there are attached buildings with one or two façades only, and this facade may be the northern one, where the sun shines on it slightly. On the contrary, one of the most important features of the building's rooftop is the sun shining on it all over the day, and it is flat, which facilitates controlling the tilt angle of photovoltaic panels to the best degree to achieve the highest possible efficiency and the largest possible amount of energy. Therefore, compared to other systems [21], the result is that roofs are ideally suited for BIPV integration, usually, there is less shadowing at roof height than at ground level. Roofs often provide a large, unused surface for integration. Thus, nowadays a BIPV or PV system is widely used on roofs because of a lot of advantages of roofing integration when we integrate BIPV on the roof system, we achieve more power than the ground level and no shadowing effect and hence the efficiency of the BIPV is increased. Hence, the most appropriate choice was to use a building rooftop to use photovoltaic panels.

To achieve multifunctional roles for BIPV systems, various factors should be considered, such as the PV module temperature, shading, installation angle, and orientation. Among these factors, the irradiance and PV module temperature should be regarded as the most important factors because they affect both the electrical efficiency of the BIPV system and the energy performance of buildings, where BIPV systems are installed [16]. The results of basic studies on the irradiance and energy output of PV systems have been reported by some researchers, while there have been other studies on the temperature and generation performance of PV modules, worth noting that most of these studies relate to most European countries or related to the cold climate, whereas there is a lack of studies considered Arabic region [11]. Therefore, this study aims to investigate the potential of PV systems in the residential sector of Hail city by focusing on the buildings' rooftop. The key objectives of the work are: (i) to estimate the total rooftop area in Hail, utilizable for PV application; (ii) to investigate the performance ratio and the system efficiency related to the local conditions; (iii) to determine the optimum tilt angle to achieve the largest possible amount of energy; as well as (iv) to determine the power generation potential from the rooftop PV application when using all effective roof area in the Hail city, (v) to estimate the amount of CO_2 emissions that could be reduced as a result of using PV system. Based upon the latest census, building rooftop areas are estimated. The performance ratio and the system efficiency, as well as the annual energy output in several tilt angles, were determined as an indicator for PV energy generation potential for rooftop areas considering local building construction. Taking into consideration Hail City as a case study.

2. The Status of the Energy in KSA

According to the Electricity and Cogeneration Regulatory Authority, the maximum load demand has increased in Saudi Arabia from 51,939 MW to 62,121 MW during the period 2012–2017, with an increase of nearly 3.27% per year. Consequently, the installed generating capacities have also increased, as they reached 80,471 MW in 2017 compared to 53,588 in 2012, with an increase of 51%. Moreover, the produced energy has increased in Saudi Arabia from 271,678 GW/h in 2012 to 355,080 GW/h. This increase is the result of the development in energy consumption as it reached 298,440 GW/h in 2017 compared to 246,613 GW/h in 2012. In the same context, the residential sector is the largest electricity-consuming sector in the Kingdom, where it consumes about half of the electricity consumed in the Kingdom (as shown in Table 1).

Table 1. Electricity Consumption by Sector from 2012 to 2017 (GW/h).

Year	Residential	Commercial	Governmental	Industrial	Other	Total
2012	120,652	39,934	26,354	46,627	13,046	246,613
2013	126,113	39,648	27,644	55,636	13,642	262,683
2014	136,367	42,949	30,280	56,618	14,939	281,153
2015	144,512	47,163	39,673	51,857	11,406	294,611
2016	143,661	48,225	38,498	53,587	12,702	296,673
2017	143,473	48,349	38,666	54,863	13,089	298,440

Source: The Electricity and Cogeneration Regulatory Authority.

Saudi Arabia has been blessed with vast amounts of sunlight; the Kingdom has one of the world's highest levels of solar radiation. However, the Kingdom generates only a very small amount of solar energy electricity, which constitutes only a marginal proportion of its electricity production, as its power stations depend mainly on fossil fuel (as shown in Table 2).

Table 2. Development of Produced Electricity (GW/h) by Type of Production.

Year	Steam Generators	Gas Generators	Combined Cycle Generators	Diesel Generators	Solar	Other	Total
2017	95,367	51,854	57,127	2,587	0.6	148,144	355,080

Source: The Electricity and Cogeneration Regulatory Authority.

One of the most important elements to preserve the natural environment is to balance the exploitation of its resources to meet the requirements of life for future generations and achieve economic development. Saudi Arabia, like any other country, tries to find alternative energy sources to go along with the Saudi vision 2030 in the production of electricity by using renewable energy sources. The National Renewable Energy Program (NREP) has been launched under the umbrella of the Saudi Vision 2030 and the National Transformation Program. It aims to sustainably increase the renewable energy share of total energy sources in Saudi Arabia to reach 3.45 GW by 2020—approximately 4% of Saudi Arabia's total energy production, and 9.5 GW by 2023—10% of total energy production [22].

3. Solar Energy in the Study Area

Hail is located at 27.4° north latitude and 41.7° east longitude, on 1000 m above sea level, it is considered one of the typical examples of a desert climate. This climate is BWh according to the Köppen–Geiger climate classification. The average annual temperature is 20.9 °C, and about 174 mm of precipitation falls annually. Figure 1 shows the maximum and minimum monthly outdoor temperature all over the year [23].

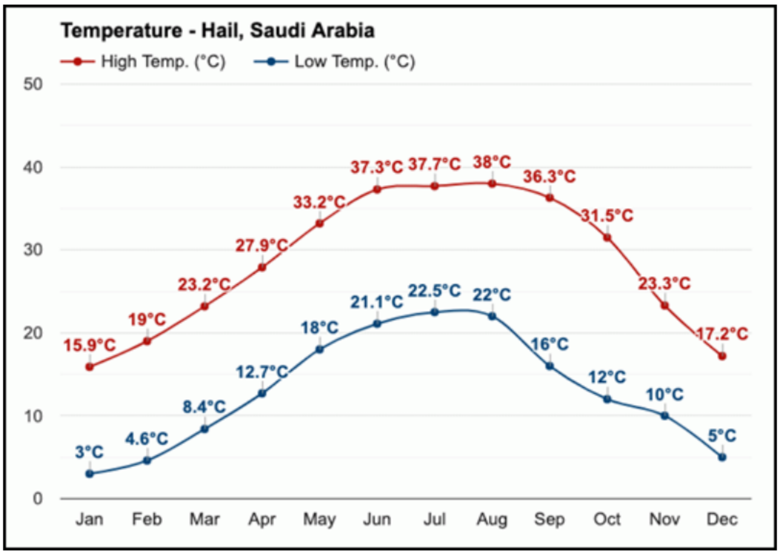
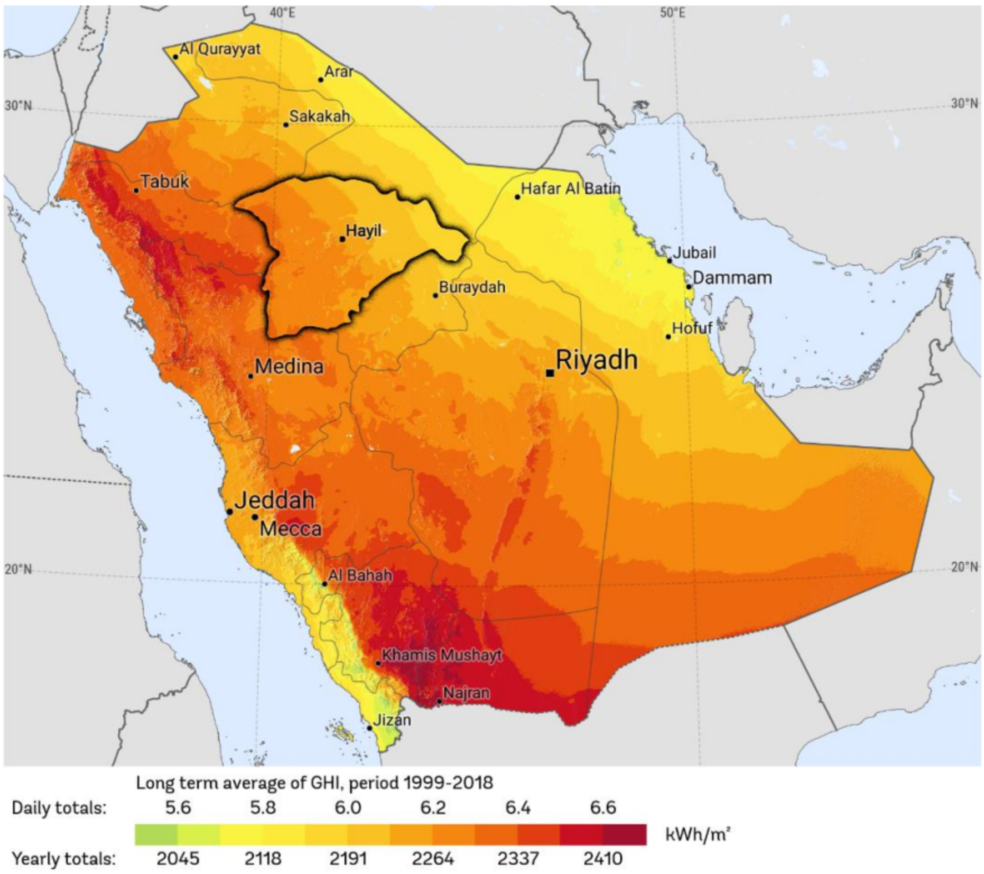


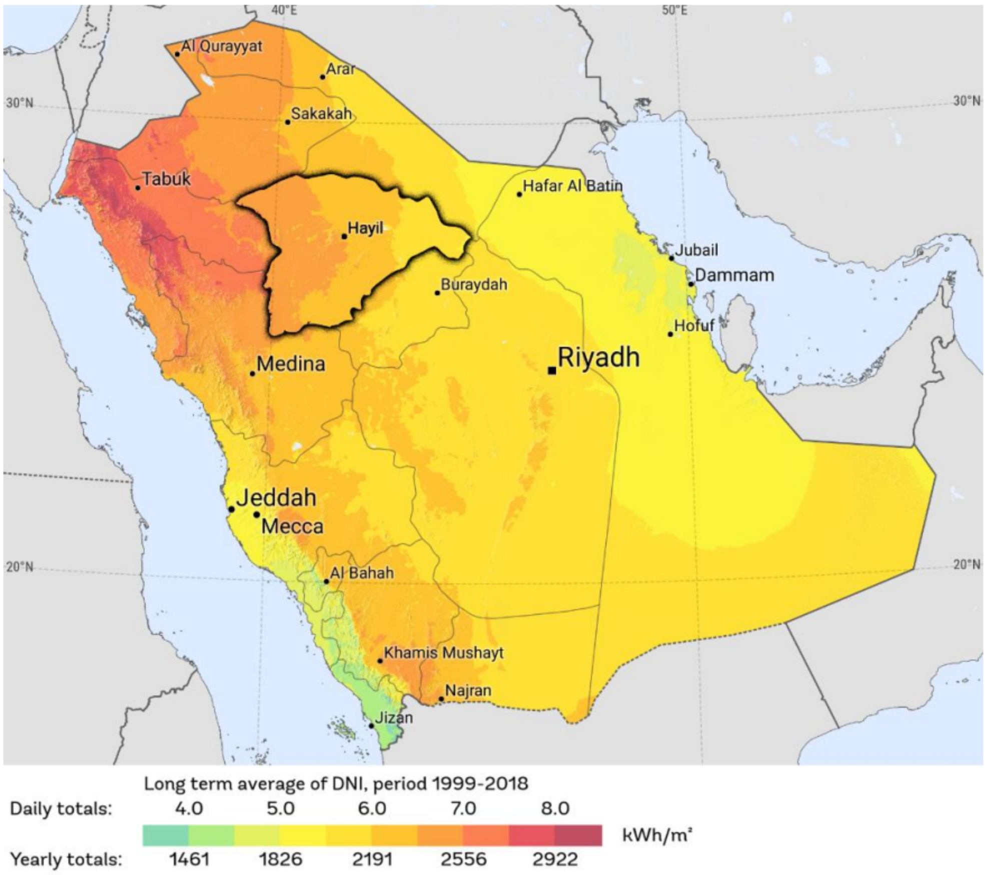
Figure 1. Maximum and minimum monthly temperature—Hail.

The geographical location of Saudi Arabia is well placed for capitalizing solar energy with the average daily solar radiation level reaching 6 kWh/m^2 and 80–90% of clear sky days over the year. The annual solar radiation level reaches over 2400 kWh/m^2 (as shown in Figure 2).



(**a**)

Figure 2. *Cont.*



(**b**)

Figure 2. The annual solar Irradiance map for KSA [24]: (**a**) Global Horizontal Irradiance (GHI); (**b**) Direct Normal Irradiance (DNI).

According to data collected in King Abdullah City for Atomic and Renewable Energy (K.A.CARE) in 2017, Hail in the northern region receives a considerable daily average of global, direct, and diffused solar radiation equal to 5.359 kWh/m^2/day, 4.884 kWh/m^2/day and 2.261 kWh/m^2/day respectively. Therefore, it is normal to see that the percentage of houses using solar energy in 2018 was about (1.45%) at the Kingdom's level, and Hail has the highest value of using solar energy (2.80%), moreover, Bahah recorded the lowest percentage of using solar energy in Saudi Arabia with (0.59%).

4. Estimation of the Rooftop Areas in Hail City

The rooftop area for PV application was calculated with the help of the latest data available about residential buildings through the Housing Statistics Bulletin 2019 [25]. The statistics database gives the number/type of housing units occupied by Saudi households in Hail, where the total number of units occupied by Saudi households reached 14,241, 34,675, and 31,825 for apartments, villa, and traditional houses respectively.

The actual size of the housing units as per category is very difficult to know, but an excerpt from the study conducted between 2010–2012 titled as the National Housing Strategy in the Kingdom of Saudi Arabia(The Saudi General Housing Authority (GHA) cooperated with the German corporation Gesellschaft für Internationale Zusammenarbeit (GIZ) to prepare the National Housing Strategy under its supervision.), gives us a brief estimate as in (Table 3), which shows the range of floor area distribution of living space of each type of housing unit [8].

Table 3. Distribution of living space by floor area.

Floor Area (m^2)	Mean (m^2)	Apartment	Villa	Traditional House
Less than 50	25	3%	0%	6%
50–99	74.5	32%	3%	41%
100–149	124.5	39%	7%	29%
150–199	174.5	16%	13%	13%
200–249	224.5	7%	22%	10%
250–299	274.5	3%	18%	1%
300–349	324.5	0%	16%	0%
More than 350	400	0%	21%	0%
Total		100%	100%	100%

Multiplying the number of units for each type (apartments, villa, and traditional houses) by the percentage of each area category (indicated in Table 3), we get the number of units and then multiplying it by the mean area of each category, we get the total area for each category separately, as shown in (Table 4) which indicate the number of units and the equivalent area of each category.

Table 4. The floor area of each housing type as per category.

	Apartment		Villa		Traditional House	
	No. of Units	Area (m^2)	No. of Units	Area (m^2)	No. of Units	Area (m^2)
Less than 50	427.2	10,680.7	0	0	1909.5	47,737.5
50–99	4557.1	339,505.4	1040.3	77,498.6	13,048.3	972,094.6
100–149	5553.9	691,471.7	2427.3	302,192.6	9229.3	1,149,041.6
150–199	2278.5	397,608.7	4507.8	786,602.4	4137.3	721,950.1
200–249	996.8	223,797.3	7628.5	1,712,598.3	3182.5	714,471.3
250–299	427.2	117,274.6	6241.5	1,713,291.8	318.3	87,359.6
300–349	0	0	5548.0	1,800,326.0	0	0
More than 350	0	0	7281.8	2,912,700.0	0	0
Total	14241.0	1,780,338.6	34,675.0	9,305,209.6	31,825.0	3,692,654.8

Each traditional housing unit is usually comprised of a ground floor, but a villa or apartment has several floors. Hence, the number of housing units, especially villas and apartments, does not project the total usable roof area. This correction of the number of housing units under one building is to be made before proceeding further.

According to the housing statistics database issued by the General Authority for Statistics (GAStat), the number of villas is almost half the value of the housing units for each villa. Hence, it can be assumed that each villa consists of an average of two floors. Similarly, for apartment housing units, it is a norm in Saudi Arabia to build a three-floor residential building unit with two to six housing units on each floor. Based on the previous data, the usable roof area can be recalculated (as shown in Table 5), where the rooftop area of villas will be reduced to about half of the total area of villa units, it can be expressed in the following equation.

$$\textit{Total Corrected Area (Villas)} = \textit{Total Original Area (Villas)}/2 \quad (1)$$

Table 5. The total and corrected floor area of each housing type.

	Apartment	Villa	Traditional House	Total
Total original area (m^2)	1,780,338.62	9,305,209.62	3,692,654.75	14,778,202.99
Total corrected area (m^2)	712,135.45	4,652,604.81	3,692,654.75	9,057,395.01

As well as usable roof areas of the apartment will be found to be about 40% of the original area, which can be expressed as:

$$Total\ Corrected\ Area\ (Apartment) = Total\ Original\ Area\ (Apartment) \times 0.4 \quad (2)$$

While the traditional house area will be unchanged.

Therefore, the total area to study the feasibility of rooftop PV potential in residential buildings in Hail exceeds 9 million square meters, taking into consideration that this area for the residential buildings occupied by Saudi households, which represents about 65% of the total residential buildings (according to GAStat). However, this value is not an effective rooftop area, where shadows due to rooftop construction, parapet walls, patio covers, etc. should be considered and the cultural aspects as well.

5. Selecting the Simulation Tool

A technique, which can be employed to achieve the aim of the research, is modeling and simulation. Many simulation tools have been developed, ranging from research-grade software to commercial products. Confidence in PV models helps projects secure more accurately characterize the expected performance. Multiple photovoltaic performance modeling tools can be used to model PV systems, such as System Advisor Model (SAM), PVWatts, PVsyst, and PV*SOL. These tools were chosen due to their popularity. While the tools implement many of the same internal sub-models, the inputs accepted and/or required for these tools differ slightly. The differences between expected inputs may indicate the complexity of the tools, as well as the aspects that each tool specializes in modeling [26]. A report issued by National Renewable Energy Laboratory (NREL) [27] highlights the distinction between the three detailed performance modeling tools (SAM, PVsyst, and PV*SOL), and the simpler tool, PVWatts. PVWatts underestimates all systems due to its much higher default loss assumption compared to the detailed tools, it is considered more simple than other tools. On the other hand, among the three detailed performance modeling tools (System Advisor Model (SAM), PVsyst, and PV*SOL), all annual errors were within ±8% and all hourly Root Mean Square Error (RMSEs) were less than 7% for all systems.

*Experimental Validation for PV*SOL under the Condition of Hail City*

To consolidate the results and achieve better accuracy, the experimental validation of the simulation program was carried out by comparing the simulation results with field measurements, A practical sized solar panel with nominal 80 W output was used for this experiment, and the solar panel is connected to a control panel containing relevant instrumentation and a battery charge control system. The solar panel was supplied with an adjustable stand that allows inclination to be varied. This allowed the irradiance incident on the panel (kW/m^2) to be measured and compared with the electrical power generated, along with system efficiency (Figure 3). As such, the energy output of an off-grid system was measured. The system was set up according to the VDAS® (Versatile Data Acquisition System); a standard arrangement of a multi-crystalline photovoltaic panel array, battery storage, and a solar charge controller. Measurements were taken under a clear sky on 15–17 March 2020.

Figure 3. Field measurements of an off-grid PV system with different tilt angles (0°, 30°, and 60°).

These measured values were then compared to the values derived using PV*SOL for the same days of measurements and the same type of PV panels to validate PV energy output (Figure 4). Although the climate data used in PV*SOL software were extracted through MeteoSyn, which provides site-dependent climate data, by selecting the location on the map, then selecting the Meteonorm climate data source, where the Typical Meteorological Year (TMY) for any site is the main result. However, in the present study, climate data measured (on the same days on 15–17 March 2020) by the weather station installed at the College of Engineering—University of Hail were used. As PV*SOL software gives this feature, thanks to the MeteoSyn module which offers the possibility to select already existing climate locations and to create new ones. So, new records can be imported, and the database updated. New locations or climate data can be generated by creating a new location option.

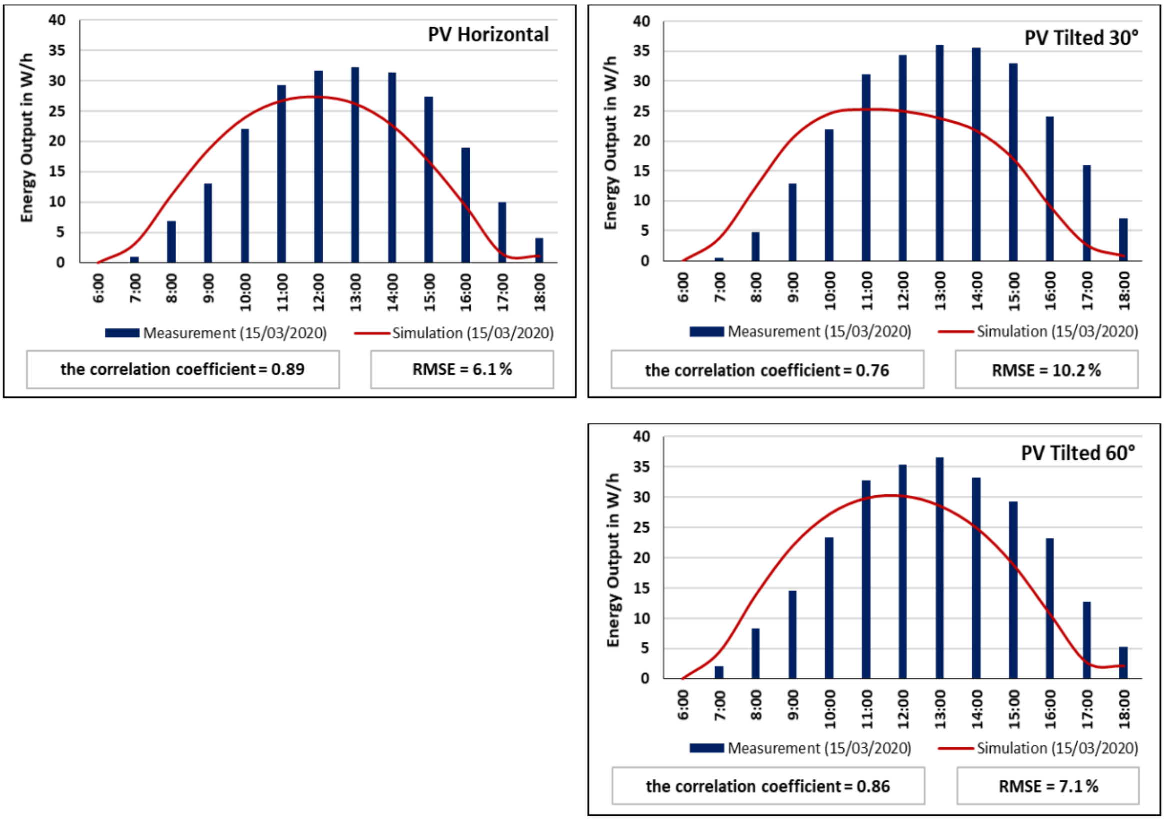


Figure 4. Validation of the energy output of the tilted model over three days.

The correlation coefficient (ρ) was calculated for each day separately, which recorded 0.89, 0.76, and 0.86, respectively.

$$\rho_{xy} = \frac{\text{cov}(x, y)}{\sigma_x \sigma_y} \tag{3}$$

where:

ρ_{xy} = Pearson product-moment correlation coefficient
cov(x,y) = covariance of variables x and y
σ_x = standard deviation of x
σ_y = standard deviation of y

ASHRAE developed (Guideline 14) strongly recommends that the root mean square error (RMSE) should be less than 30% to validate a PV energy model.

$$RMSE \frac{\sqrt{\sum_{i=1}^{n} (Pi - Oi)^2}}{n} \tag{4}$$

where:

$RMSE$ = the root mean square error
Pi = Predicted values
Oi = Observed values
n = Number of observations

Where the (RMSE) of the 0° tilted model was 6.1%, 9.9% for the 30° tilted model, and 7.1% for the 60° tilted model. These results are also close to those of calibration carried out by (NREL), which indicates that the Root Mean Square Error (RMSE) was less than 7% for all systems including PV*SOL.

The results are very convergent between the simulation and the measurements in the three experimental days. It is axiomatic to note the difference between the measurements and the simulation results, but it can be due to the difference between some elements used in the simulation and its peers in nature. Therefore, the PV*SOL simulation program seems a suitable tool to use in the present research to predict the potential of PV system performance.

6. The System Design

The PV*SOL simulation program was used to create a typical model for a flat roof with a surface area equal to 200 m^2. The array was designed based on the architecture design of the house and upon the roof (Figure 5). The system was designed for maximum output in several tilt angles within the range from 0° to 75° with 15° intervals. Different configurations were made for stand-alone PV systems, which enabled the planning of an off-grid PV system with electric consumers and battery inverters with batteries; the roof-mounted system was designed for Hail conditions.

The system characteristics are represented as shown in (Table 6), as well as the example of the mounted-roof PV system shown in (Figure 6).

The roof was directed towards the north. According to the geographical studies of Hail city. which is located in the northern hemisphere, also taking into consideration the sun path diagram of Hail city (Figure 7), this implies that the solar panel could be mounted facing south to capture a maximum amount of solar energy.

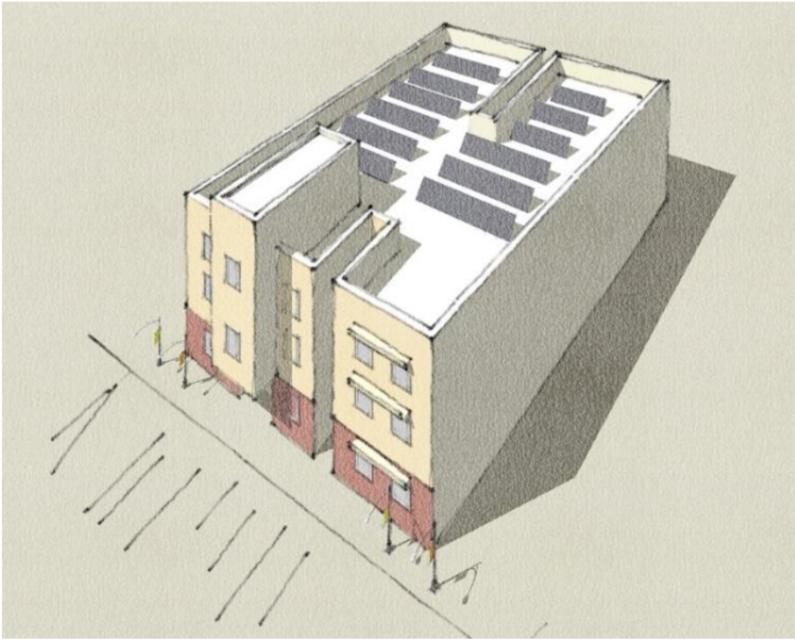


Figure 5. Installation photovoltaic module.

Table 6. PV system characteristics.

Type of System	Stand-alone PV system
Installation Type	Mounted-Roof
Roof Area	200 m^2
PV Generator Surface	48.8 m^2
Number of PV Module	30
PV Generator Output	8.4 kWh
Orientation	180°
Inclination	0, 15, 30, 45, 60, and 75

Figure 6. Example of mounted-roof PV system.

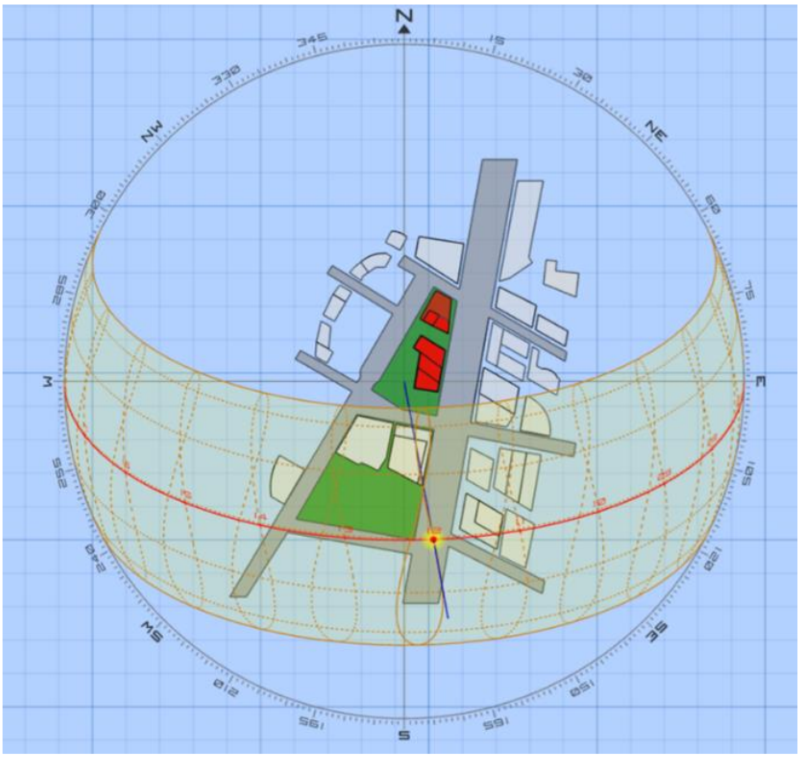


Figure 7. Sun path diagram—Hail.

7. Results and Discussion

To predict the potential of PV system performance, the PV*SOL software was used. The simulation procedures were carried out by preparing the simulation model and calculate the performance ratio and the system efficiency for several tilt angles.

7.1. Performance Ratio

The performance ratio is the final yield divided by the reference yield. The performance ratio is affected by irradiation, panel temperature, availability of grid, size of the aperture area, nominal power output, and temperature correction values [28].

$$PR = YF/YR \tag{5}$$

where, *YF* is the final yield which is the annual, monthly, or daily net AC energy output of the system divided by the peak power of the installed PV array at standard test conditions, and calculated as $YF = E_{PV,\ AC}/P_{max}$

YR is the reference yield, which is the total in-plane irradiance H divided by the photovoltaic's reference irradiance G and calculated as $YR = Ht/G_o$.

7.2. System Efficiency

The instantaneous system efficiency is given as PV module efficiency multiplied by the inverter efficiency [28].

$$\mu_{sys,\ T} = \mu_{PV.\ T} \times \mu_{inv.\ T} \tag{6}$$

As shown in (Table 7 and Figure 8), it was found that the more the system is tilted, the higher the performance ratio and the system efficiency, although the amount of solar radiation decreases with the increase in the inclination. Therefore, this leads us to another point worth noting, which is the relation between the irradiance module temperature, and system efficiency.

Table 7. Performance ratio and system efficiency in several tilt angles.

Angle	Performance Ratio (%)	System Efficiency (%)
0	41.4	14.9
15	38.5	14.8
30	37.6	15.1
45	38.7	15.6
60	42.3	16.3
75	47.1	18.5

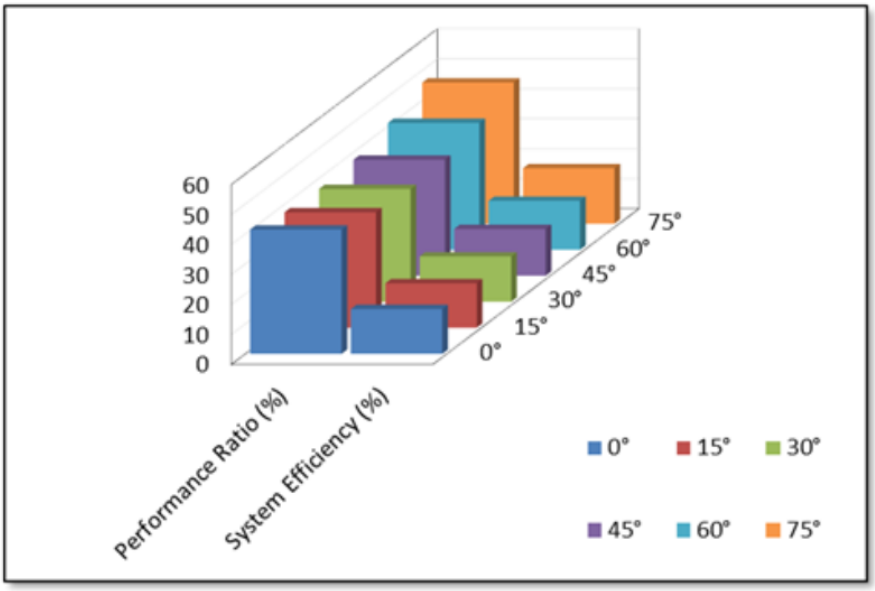


Figure 8. Performance ratio and system efficiency in several tilt angles.

Figure 9 shows the existence of a direct correlation between the irradiance and the temperature of the PV module, as the lower the irradiance, the lower the PV module temperature and vice versa, therefore, by linking with Table 7, we find that with the decrease in the PV module temperature, its efficiency increases.

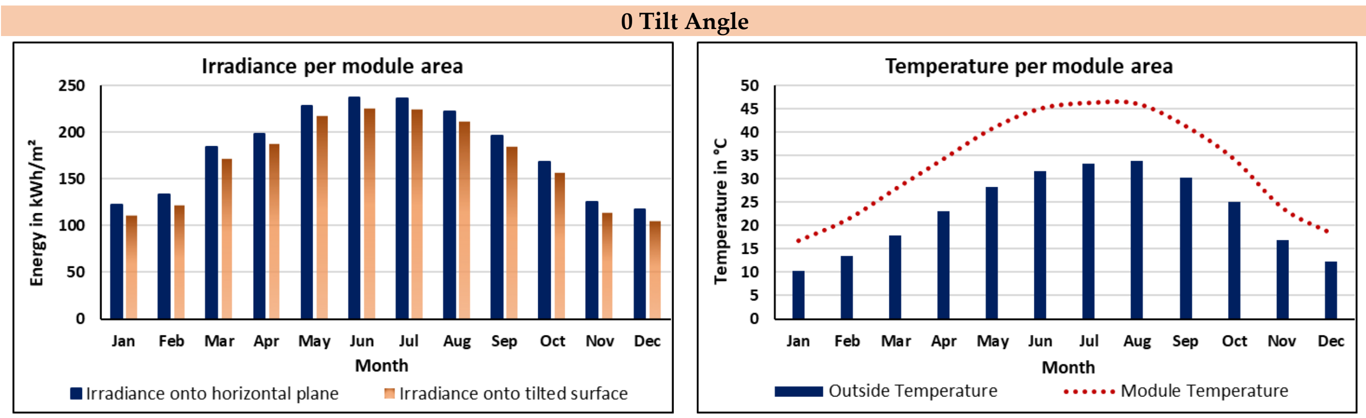


Figure 9. *Cont.*

Figure 9. *Cont.*

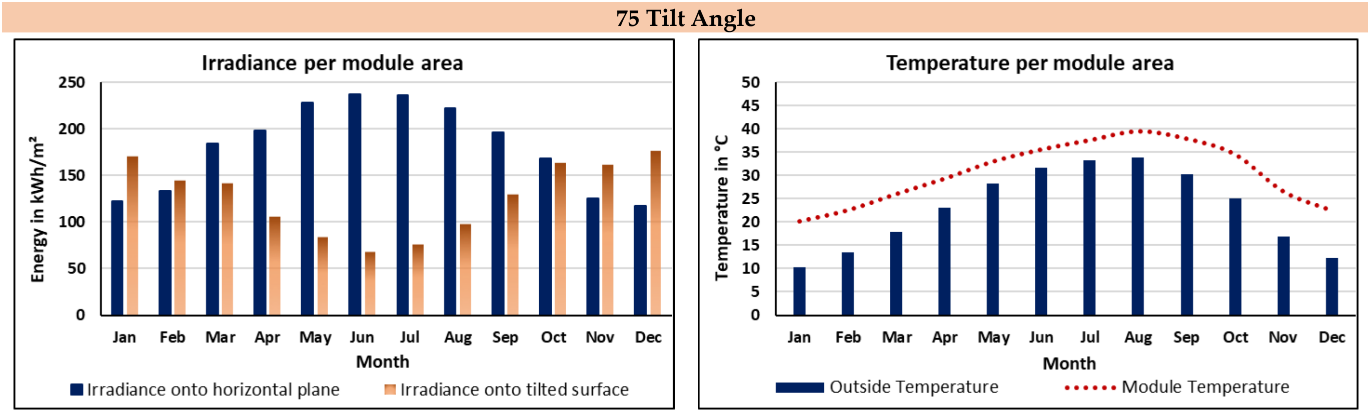


Figure 9. The relationship between the irradiance and the temperature of the PV module.

From the previous results, it was found that the conversion efficiency is the most important characteristic of a photovoltaic panel; this efficiency is translated by the amount of irradiance that is transformed into electrical power. In PV cells, the energy efficiency is on average 14% and 17% [29,30], and so the irradiance that is not converted into electricity is often transformed into heat. The manufacturers and a lot of research work [29–31] confirm the decrease of efficiency while the temperature of PV cells rises. It is confirmed that the maximum power produced varies linearly with the effective temperature.

7.3. Annual Energy Output

The 8.4 kWp PV system has 30 PV modules with a total area of 48.8 m^2. The modules are free from any effect of shade and are mounted on a flat roof facing south. The annual energy output of a photovoltaic installation can be calculated as:

$$E = Pstc \times Hi \times PR \tag{7}$$

where,

E = Annual energy output (kWh/year)

Hi = global incident radiation (kWh/m^2/year)

Pstc = peak power at STC conditions of photovoltaic solar panels (kWp)

PR = Performance ratio of the solar PV system

Using Equation (7), several results were obtained (Figure 10). The results indicate that the 30° tilt PV produced the highest amount of energy as 7662.3 kWh/year recorded, whereas the 75° tilt PV records the smallest one with 6041.4 kWh/year, although it achieves the best possible efficiency.

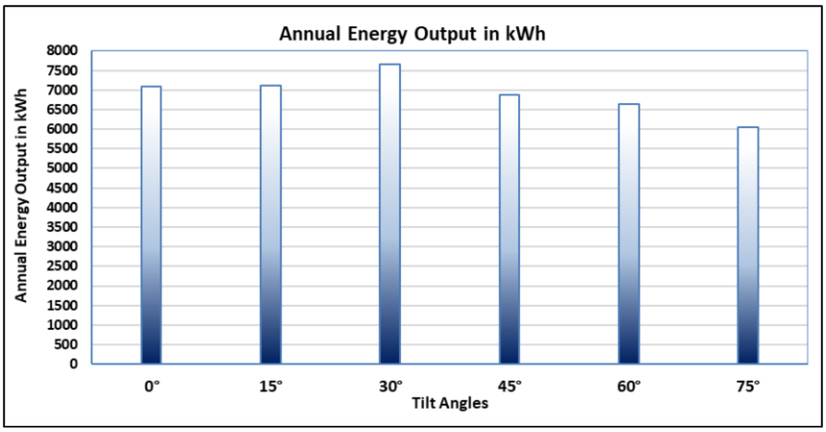


Figure 10. The yearly energy output of different tilt angles.

From the previous results, we find that the best inclination is 30°, which achieves annual energy of 7662.3 kWh, it is the result of 48.8 m^2 of the rooftop PV system, which is considered the effective area of the building rooftop extracted from 200 m^2 by the ratio reach to 24.4%. Besides, back to the total area suitable for using photovoltaic panels in the city of Hail, which is estimated at 9 million square meters, and by applying the previous percentage, we find that the effective area for using photovoltaic panels on the roofs of residential buildings in Hail is equal to 2,210,004.38 m^2.

On the other hand, the energy produced per square meter of photovoltaic panels can be calculated as follows: Annual Energy output (kWh)/PV Surface Area (m^2)

Therefore, the energy output per square meter of PV = 7662.3/48.8 = 157.0 kWh/m^2, so the total energy that can be obtained from the roofs of the residential buildings in Hail is estimated to be 2,210,004.38 × 157.0 = 346,970 kWh (346.97 GWh), which considered a significant amount of energy produced from the use of all residential rooftop in Hail.

7.4. GHG Emission Reduction

Referring to the amount of CO_2 that can be reduced by using the PV system, despite its prodigious solar potential, Saudi Arabia generated more than 99% of its electricity using fossil fuels. The Saudi electricity sector has developed quickly over the past decade, both in terms of growth and in the fuel mix. Where (Table 8) presents the amounts of fuels being used for electricity generation in the year 2017, these values consider the fuels used for co-generation.

Table 8. Electricity generation by source in Saudi Arabia.

Type of Fuels	Percentage
Natural gas	50.7%
Crude oil	24.2%
Heavy fuel oil	16.5%
Diesel	8.6%

Source: The Electricity and Cogeneration Regulatory Authority.

Using RETScreen tools, the GHG emission factor values were extracted, which were 0.47, 1.01, 1.19, and 1.08 $kgCO_2/kWh$ for natural gas, crude oil, heavy fuel oil, and diesel respectively. On the other hand, the GHG emission factor for the electricity mix equal to 0.77 $kgCO_2/kWh$. Therefore, the yearly emission of CO_2 can be evaluated as [32]:

$$CO_2 \textit{ emission per year} = \textit{Energy Output} \times 0.77 \tag{8}$$

Therefore, in the present case,

CO_2 emission per year = 7662.3 × 0.77 = 5899.9 $kgCO_2$ per year

This amount is also a significant reduction in the amount of CO_2 emissions.

From the above, it can be said that several factors are affecting the amount of energy produced from the PV system, such as the degree of system tilt, orientation, the temperature of the system as well as its efficiency are different factors, but they must be linked together innovatively and distinctively to produce the largest possible amount of energy.

8. Conclusions

This paper outlines the investigations carried out to determine the potential of BIPV technology integrated into the building rooftop in Hail City. The investigation of BIPV technology is a complicated process as the BIPV modules have multifunctional features related to the aesthetic and technological integration in the building envelope and the energy integration in the building system. Therefore, there is the need to overcome the technical, architectural, and social barriers to reach a larger scale of BIPV applications and thus improve their economic profitability.

The first issue to deal with is to study the rooftop solar PV potential, as well as identifying the amount of rooftop area that is suitable for PV. This study examined the potential of PV systems in the residential sector of Hail City, focusing on the buildings' rooftop. Therefore, the total area suitable for installing the PV system in Hail City exceeds 9 million square meters, taking into consideration that this area for the residential buildings occupied by Saudi households (65% of total residential buildings). However, this value is not an actual rooftop area, where shadow and cultural aspects should be considered to reduce this value.

Secondly, it is important to better investigate the power generation potential from the rooftop PV application, so the experimental validation of the simulation program is carried out by comparing the simulation results with field measurements. The results are very convergent between the simulation and the measurements in the three experimental days with different tilt angles. It is axiomatic to note the difference between the measurements and the simulation results, but it can be due to the difference between some elements used in the simulation and its peers in nature. After that, a comprehensive analysis of the performance ratio and the system efficiency of an off-grid system in several tilt angles was carried out, as an indicator for PV energy generation potential for rooftop areas considering local building construction. It can be said that the performance ratio and the system efficiency were affected by the tilt angle of the PV module, where the efficiency increases with higher tilt angle, this is due to the PV module temperature, where, with the decrease in the PV module temperature its efficiency increases. Besides, the results pointed out that the 30° tilt PV produced the highest amount of energy, whereas the 75° tilt PV records the smallest one although it achieves the best possible efficiency. There is a considerable amount of energy production from the use of all residential rooftops in Hail, reaching more than 346 GWh, and there is also a significant reduction in the amount of CO_2 emissions, reaching nearly 5.9 t CO_2 per year.

This study contributes to the knowledge of PV system integration into residential buildings rooftop in Hail City. Policymakers and scientists may utilize the results of this research. In conclusion, the integration of PV systems into the rooftops of the residential buildings offers a considerable amount of clean and renewable energy potential that could slightly move towards achieving the concept of zero-energy buildings and contribute to lower CO_2 emissions, which are considered the most important objectives of Saudi Arabia's Vision 2030.

List of Abbreviation

$cov_{(x,y)}$	Covariance of variables x and y
E	Annual energy output
Hi	Global incident radiation
n	Number of observations
Oi	Observed values
Pi	Predicted values
PR	The performance ratio
$Pstc$	Peak power at STC conditions of photovoltaic solar panels
R	Conversion efficiency
$RMSE$	Root mean square error
Y_F	The final yield
Y_R	The reference yield
$\mu_{(inv.T)}$	The inverter efficiency
$\mu_{(PV.T)}$	PV module efficiency
$\mu_{(sys,T)}$	Instantaneous system efficiency
ρ_{xy}	Pearson product-moment correlation coefficient
σ_x	Standard deviation of x
σ_y	Standard deviation of y

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References

1. Nguyen, H.T.; Pearce, J.M. Estimating potential photovoltaic yield with r.sun and the open source Geographical Resources Analysis Support System. *Solar Energy* **2010**, *84*, 831–843. [CrossRef]
2. IEA, *World Energy Outlook 2014*; IEA: Paris, France, 2014; Available online: https://www.iea.org/reports/world-energy-outlook-2014 (accessed on 20 June 2020).
3. Salam, M.A.; Khan, S.A. Transition towards sustainable energy production—A review of the progress for solar energy in Saudi Arabia. In *Energy Exploration and Exploitation*; SAGE Publications Inc.: Thousand Oaks, CA, USA, 2018. [CrossRef]
4. IEA. *World Energy Outlook 2019*; IEA: Paris, France, 2019; Available online: https://www.Iea.Org/Reports/World-Energy-Outlook-2019 (accessed on 20 June 2020).
5. Zell, E.; Gasim, S.; Wilcox, S.; Katamoura, S.; Stoffel, T.; Shibli, H.; Engel-Cox, J.; Subie, M.A. Assessment of solar radiation resources in Saudi Arabia. *Sol. Energy* **2015**, *119*, 422–438. [CrossRef]
6. Climate Transparency. The G20 Transition towards a Net-Zero Emissions Economy. *Clim. Transpar.* **2019**, *53*, 1689–1699. Available online: http://www.climate-transparency.org/g20-climate-performance/g20report2019 (accessed on 5 July 2020).
7. Felimban, A.; Prieto, A.; Knaack, U.; Klein, T.; Qaffas, Y. Assessment of current energy consumption in residential buildings in Jeddah, Saudi Arabia. *Buildings* **2019**, *9*, 163. [CrossRef]
8. Khan MM, A.; Asif, M.; Stach, E. Rooftop PV potential in the residential sector of the kingdom of Saudi Arabia. *Buildings* **2017**, *7*, 46. [CrossRef]
9. Owusu, P.A.; Asumadu-Sarkodie, S. A review of renewable energy sources, sustainability issues and climate change mitigation. *Cogent Eng.* **2016**. [CrossRef]
10. Matar, W.; Murphy, F.; Pierru, A.; Rioux, B.; Wogan, D. Efficient industrial energy use: The first step in transitioning Saudi Arabia's energy mix. *Energy Policy* **2017**, *105*, 80–92. [CrossRef]
11. Heinstein, P.; Ballif, C.; Perret-Aebi, L. Building Integrated Photovoltaics (BIPV): Review, Potentials, Barriers and Myths. *Green* **2013**, *3*, 125–156. [CrossRef]
12. Marszal, A.J.; Heiselberg, P.; Bourrelle, J.S.; Musall, E.; Voss, K.; Sartori, I.; Napolitano, A. Zero Energy Building—A review of definitions and calculation methodologies. *Energy Build.* **2011**, *43*, 971–979. [CrossRef]
13. Al-Tamimi, N.A.; Fadzil, S.F.S. The potential of shading devices for temperature reduction in high-rise residential buildings in the tropics. In *Procedia Engineering*; Elsevier Ltd.: Amsterdam, The Netherlands, 2011; Volume 21, pp. 273–282. [CrossRef]
14. Palmero-Marrero, A.I.; Oliveira, A.C. Evaluation of a solar thermal system using building louvre shading devices. *Sol. Energy* **2006**, *80*, 545–554. [CrossRef]
15. Jelle, B.P.; Breivik, C. State-of-the-art building integrated photovoltaics. *Energy Procedia* **2012**, *20*, 68–77. [CrossRef]
16. Pelle, M.; Lucchi, E.; Maturi, L.; Astigarraga, A.; Causone, F. Coloured BIPV technologies: Methodological and experimental assessment for architecturally sensitive areas. *Energies* **2020**, *13*, 4506. [CrossRef]
17. Lucchi, E.; Polo Lopez, C.S.; Franco, G. A conceptual framework on the integration of solar energy systems in heritage sites and buildings. *IOP Conf. Ser. Mater. Sci. Eng.* **2020**. [CrossRef]
18. United Nations (ESCWA). Addressing Energy Sustainability Issues in the Buildings Sector in the Arab Region. 2018. Available online: https://www.unescwa.org/sites/www.unescwa.org/files/publications/files/addressing-energy-sustainability-issues-buildings-sectori-arab-region-english_0.pdf (accessed on 5 July 2020).
19. Eissa, M.A. Improving the Built-Environment with Sustainable Ecosystems Assistance in the Hot Regions. *JKAU Environ. Des. Sci.* **2009**, *6*, 111–121. [CrossRef]
20. Eissa, M.A. Sustainable Urban Development as an Approach to Rehabilitation of Historical Jeddah City. *JKAU Environ. Des. Sci.* **2005**, *4*, 103–123. (In Arabic) [CrossRef]
21. Debbarma, M.; Sudhakar, K.; Baredar, P. Comparison of BIPV and BIPVT: A review. *Resour. Effic. Technol.* **2017**, *3*, 263–271. [CrossRef]
22. Indicators of Renewable Energy in Saudi Arabia 2017; General Authority for Statistics, KSA. 2017. Available online: https://www.stats.gov.sa/sites/default/files/indicators_of_renewable_energy_in_saudi_arabia_2017_en_2.pdf (accessed on 17 June 2020).

23. Hail Climate: Average Temperature, Weather by Month. Available online: https://en.climate-data.org/asia/saudi-arabia/ha-il-region/hail-34016/ (accessed on 17 June 2020).
24. Global Solar Atlas. Available online: https://globalsolaratlas.info/download/saudi-arabia (accessed on 16 June 2020).
25. Available online: https://www.stats.gov.sa/sites/default/files/housing_bulletin_semi_annual_2018_en.pdf (accessed on 19 June 2020).
26. Freeman, J.; Whitmore, J.; Blair, N.; Dobos, A.P. Validation of multiple tools for flat plate photovoltaic modeling against measured data. In Proceedings of the 2014 IEEE 40th Photovoltaic Specialist Conference (PVSC), Denver, CO, USA, 8–13 June 2014; pp. 1932–1937. [CrossRef]
27. NREL. *Validation of Multiple Tools for Flat Plate Photovoltaic Modeling against Measured Data*; Technical Report (NREL/TP-6A20-61497); National Renewable Energy Laboratory: Golden, CO, USA, 2014. Available online: https://www.nrel.gov/publications (accessed on 6 September 2020).
28. Kanchikere, J.; Ghosh, A.K.; Kumar, K. Analysis of 80 kw Grid Connected Rooftop Solar Power Plant Using Sisifo. *Int. J. Mech. Prod. Eng. Res. Dev.* **2018**, *8*, 33–46.
29. Zhao, Y.; Boccard, M.; Liu, S.; Becker, J.; Zhao, X.H.; Campbell, C.M.; Suarez, E.; Lassise, M.B.; Holman, Z.; Zhang, Y.H. Monocrystalline CdTe solar cells with open-circuit voltage over 1 V and efficiency of 17%. *Nat. Energy* **2016**, *1*, 1–7. [CrossRef]
30. Bergmann, R.B.; Berge, C.; Rinke, T.J.; Schmidt, J.; Werner, J.H. Advances in monocrystalline Si thin film solar cells by layer transfer. *Sol. Energy Mater. Sol. Cells* **2002**, *74*, 213–218. [CrossRef]
31. Skoplaki, E.; Boudouvis, A.G.; Palyvos, J.A. A simple correlation for the operating temperature of photovoltaic modules of arbitrary mounting. *Sol. Energy Mater. Sol. Cells* **2008**. [CrossRef]
32. Rajput, S.K.; Singh, O. Reduction in CO2 Emission through Photovoltaic System: A Case Study. In Proceedings of the 3rd IEEE International Conference on Nanotechnology for Instrumentation and Measurement, Greater Noida, India, 16–17 November 2017.