Article

A New Configuration of Roof Photovoltaic System for Limited Area Applications—A Case Study in KSA

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Abstract: Increased world energy demand necessitates looking for appropriate alternatives to oil and fossil fuel. Countries encourage institutions and households to create their own photovoltaic (PV) systems to reduce spending money in electricity sectors and address environmental issues. Due to high solar radiation in the Kingdom of Saudi Arabia (KSA), the government urges people and institutions to establish PV systems as the best promising renewable energy resource in the country. This paper presents an optimal and complete design of a 300 kW PV system installed in a limited rooftop area to feed the needs of the Ministry of Electricity building, which has a high energy consumption. The design has been suggested for two scenarios in terms of adjusting the orientation angles. The available rooftop area allowed to be used is insufficient if a tilt angle of 22° is used, suggested by the designer, so the tilt angle has been adjusted from 22° to 15° to accommodate the available area and meet the required demand with a minimum shading effect. The authors of this paper propose a modified scenario “third scenario” which accommodates the available area and provides more energy than the installed “second scenario”. The proposed panel distribution and the estimated energy for all scenarios are presented in the paper. The possibility of changing tilt angles and the extent of energy production variations are also discussed. Finally, a comparative study between measured and simulated energy is included. The results show that August has the lowest percentage error, with a value of 2.7%, while the highest percentage error was noticed in November.

Keywords: solar energy; PV module; power density; panel orientation; tilt angle

1. Introduction

In the last few decades, there has been a trend toward using clean energy sources in the world. Those intermittent energy sources are environmentally friendly and economical throughout the years. Developing countries, in particular, are inclined to utilize such resources to meet their energy demand. KSA is one of the highest energy-producing countries in the Middle East, with approximately 63 GW, most of which depends on oil [1–4]. This fact is considered a serious challenge for the electricity sector in the kingdom. Consequently, officials and specialists are keen to look for alternatives to address this problem adequately. Therefore, the National Renewable Energy Program in Saudi Arabia
has been established to develop and maximize the utilization of renewable energy resources and to become one of the main sources rather than depending entirely on oil.

Solar energy resources are considered the breakthrough that can highly overcome such power generation problems in most Middle East countries. Therefore, KSA is going toward increasing the use of solar energy to reduce the dependence on oil in producing energy. The average radiation in KSA ranges between 5 and 7 kWh/m²\(^2\) [1,2,4–8]. This amount of solar radiation is relatively high compared to the neighboring countries [1,9–11]. To make the use of this free and clean energy possible, the KSA government issued legislation and laws that facilitate and assist the new installations and designs of solar energy systems on the roofs of residential and commercial buildings.

Designing a PV system requires knowledge about the solar radiation theory and its calculation. The determination of the peak sun hours, which refer to the amount of energy received by the panels or, in other words, how much energy is received during the day in a specific area, is one of the most important pieces of information needed to design a PV system [3,4]. Peak power or the kilowatt peak (kWp) of the power demand has to be calculated before determining the number of panels that have to be accommodated with the roof capacity [12].

Several research studies in the literature discussed the general assessment of solar radiation resources in Saudi Arabia and the vision of the kingdom for the upcoming decade. Network design, implementation, and data quality assurance are described in [1]. In addition, the authors analyze the first year of broadband solar resource measurements from a new monitoring network in Saudi Arabia developed by the King Abdullah City for Atomic and Renewable Energy (K.A.CARE). The analysis used 12 months (October 2013–September 2014) of data from 30 stations distributed across the country based on one-minute measurements of global horizontal irradiance (GHI), diffuse horizontal irradiance (DHI), direct normal irradiance (DNI), and related meteorological parameters. In [4], the authors provide a maiden attempt to investigate how much sustainability substance is in the 2030 Vision of Saudi Arabia. The Sustainable Society Index (SSI) has been employed to examine the 2030 Vision and understand the Kingdom’s commitment to building resilient, inclusive, and sustainable societies. The Vision and National Transformation Program (NTP) texts were matched against five broad measures and 22 submeasures. Both the 2030 Vision and the NTP align with the SSI measures in some respect. The goals and objectives reflect the aspirations and context of Saudi Arabia. The carbon emission is expected to be zero in 2060 in KSA, so it is expected to be reduced by 60% in 2030 [5]. Several projects are carried out throughout the country, and different studies are presented to introduce the system regulations and policies. According to [6–10], certain policies that promote the renewable energy sector and regulate the relations with electricity and grid connection sectors are subsidized in KSA. The net metering and feed-in tariff policies are employed to exchange the surplus energy with the electricity network in KSA.

For rooftop PV systems, net-metering was tested in 2017 and found to be the most suitable policy for small-scale PV systems. The applicability of using feed-in tariff (FiT) policy in KSA is reviewed in [11], in comparison with that implemented in USA and Germany. It is concluded that KSA has the ability to adopt and use this technique.

Specific case studies in KSA have also been discussed in the literature to achieve the vision of the kingdom in the sector of solar energy. The authors in [12] examine the best tilt angle for a solar panel to maximize the collected amount of solar irradiation. A daily global and diffuse solar radiation measured on a horizontal surface is considered in this research. The optimal angle for each month allows capturing the most solar energy for the Madinah site, KSA. The authors concluded that the annual optimal tilt angle is almost equal to the location’s latitude. In [13], a comprehensive analysis is presented in order to improve the solar energy performance of residential buildings in KSA by optimizing the building envelope elements. The elements included in energy cost and energy energy-saving analysis include the wall insulation, roof insulation, window area, window glazing, window shading, and thermal mass.
Figure 1 illustrates the anticipated progress towards increasing the energy produced by renewable energy resources. Overall, the targeted capacity by 2030 would cover 58.7 GW as stated by the kingdom vision [1–3]. The plan set an initial step of producing 9.5 GW of electrical energy, followed by producing 27 GW in the next five years. By maintaining efforts, the plan is expected to be realized, as previously presented, utilizing solar, wind, and CSP energy.

When installing the PV system over buildings’ roofs, one of the significant factors that should be considered is the sun path. The more solar panels exposed to the direct sun, the more energy is harvested. Each location in the world has a specific sun path and unique tilt, azimuth, and elevation angles [12]. Figure 2 represents the most significant angles that play an important role in PV system design.
The desired tilt angle varies according to the case study under test. The designers should ensure that the solar panels face the sunlight perpendicularly, as much as possible, since the solar panels produce the highest power when they face the sun directly. During the winter semester, the solar panels face the sun at a sharp angle. Therefore, the energy produced by the PV system is low compared to the energy produced during the summer semester. In the winter semester case, the operator should ensure harvesting large amounts of solar energy by choosing proper orientation angles. The optimum tilt angle in KSA is approximately equal to the site’s latitude under test [13,14]. In addition, the elevation angle significantly affects the proper method of installing the panels with the most suitable spacing between rows. This must be determined to avoid the possibility of energy reduction that panels cause for each other. Figure 3 illustrates the relationship between elevation angle and spacing between rows in the PV system.

Figure 3. Relationship between elevation angle and spacing between rows.

Several studies consider the performance of rooftop solar panels by assessing different design and simulation methodologies. The effect of rooftop obstacles and shadow can be determined using photovoltaic software to identify the azimuth and tilt angles [15]. One study assesses the impact of a building’s shading and analyzes the available rooftop area using hillshade analysis [16]. The study estimates the potential of a rooftop system when shaded area is excluded. PV systems in rooftops and facades and a shadow algorithm are developed in [17]. It is concluded that although facades receive lower solar radiation, they have a substantial impact on potential urban PV systems once they are utilized. Mangiante et al. in [18] carried out a comparison between rooftop solar arrays in terms of neighborhood orientation and tree shadows. These obstacles affect the solar energy potential. The height and age of the trees are found to have an effect as well.

Other research studies are conducted to investigate the available areas on the surface of the urban cities [19–23]. In [19], a review systematically presents the studies that consider estimating the rooftop area of the cities and the potential deployment of rooftop PV systems. A technical and geographical assessment of the rooftop area in urban cities using novel methodology is presented in [20]. A hierarchical methodology is employed for the estimation process, which encompasses three phases of estimation: physical, geographical, and technical potentials. Geometry calculations and irradiation analysis for tilted rooftop surfaces are performed in [21], including the use of image processing for shadow estimation algorithms in different sun positions. It has been found that in large urban cities, the appropriate analysis method needs three-dimensional data of the studied location.

Many articles focus on solar capacity assessment in rooftop systems in terms of sizing, installation angles, and the efficiency of photovoltaic systems [24–28]. The complete design of a grid-connected PV system is presented in [24,28]. Performance investigation and rooftop analysis are carried out in [26–32]. In [26], a financial and technical feasibility study is performed, which is applicable for only certain geographical locations and weather
conditions. For evaluating system performance, the authors in [25] provide a photovoltaic plant design that operates with a seasonal tilt angle according to plant location. The tilt angle is set to be the same as the corresponding latitudinal value of the location to obtain the highest solar radiation. In [29], the rooftop area is assessed using the optimal tilt angle, and 60% of the area is found to be suitable for photovoltaic system implementation.

The research study in this paper aims to fill the gap by providing a comprehensive solar analysis to investigate the feasibility of establishing an on-grid PV system of 330 KW in KSA, exactly in Jeddah city, and introduce the proper building approach. The project is designed to feed the needs of the Ministry of Electricity building, which is a governmental complex with high energy-consuming appliances. The design aims to find the proper way to distribute the solar panels on the roof of the Ministry buildings. This task has been achieved by manipulating the tilt angle until obtaining the desired angle which enables the working staff to accommodate the available area with targeted production, considering that the shading must be avoided and reduced as much as possible.

The rest of the paper is organized as follows: Section 2 describes the design methodology of the PV system under test; two different scenarios are suggested in this section. The energy production for both scenarios is presented and compared. Panel orientation is discussed in Section 3, in which different orientation angles are defined and presented. The single-line diagram of the entire system is also presented in this section. PVsol simulator is used to estimate the performance ratio of this study. The size of the PV system for the second scenario is introduced in Section 4. Finally, the number of needed PV panels and inverters and the appropriate approach of connections are discussed in this section, prior to the conclusion in Section 5.

2. Design Methodology

The goal of establishing this project is to reduce the electricity bill by utilizing the empty spaces in the roof of the buildings and identifying the adequate distribution of solar panels. Table 1 shows the monthly and annual energy consumption of the building. The sizing of the project depends on the capacity of the available spaces. PVsol software was used to investigate the most appropriate orientation of PV panels. The targeted building needs 333 KW, which is the desired capacity. It is a serious challenge to accommodate such demand with a limited area. Undoubtedly, it is required for the designer to identify the proper orientation of solar panels. By adjusting the tilt angles, two scenarios were at disposal. The first scenario requires the utilization of three roofs of Ministry buildings while the second one requires only two roofs, which is the allowed case.

Table 1. Monthly and annual energy consumption of the building.

| Month   | Energy Consumption (kWh) |
|---------|--------------------------|
| January | 952,500                  |
| February| 949,100                  |
| March   | 942,000                  |
| April   | 937,500                  |
| May     | 932,500                  |
| June    | 930,100                  |
| July    | 928,100                  |
| August  | 938,100                  |
| September| 939,300                |
| October | 941,800                  |
| November| 942,500                  |
| December| 948,500                  |

Annual energy (MWh) 11,282
2.1. First Scenario

As previously mentioned, the first scenario required the space of three roofs to install PV panels due to the proposed tilt angle. The first suggestion was to adjust the tilt angle to 22° to harvest solar energy as much as possible (see Figure 4). The advantage of this approach is that the system’s efficiency is more significant than those with lower tilt angles. The optimum tilt angle differs depending on the case study under consideration. Solar panels create the most power when they face the sun directly, so designers should make sure that the panels face the sun perpendicularly as much as feasible. In addition, large space is needed to meet the desired energy capacity at the optimum tilt angle of 22° (three complete roofs as previously mentioned), but only two complete roofs are available. Therefore, the second scenario is proposed by the designer to accommodate the limitations in the roof areas.

Figure 4. Distribution of the panels in the first scenario.

2.2. Second Scenario

To face the problem of being forbidden to use the entire area, one possible solution is to change the tilt angle to reduce shading and accommodate the area restriction with targeted capacity. This was done by decreasing the tilt angle to 15° rather than 22°. This will reduce the distance between the PV panels to prevent shading and consequently reduce the entire area of installation. Figure 5 presents the distribution of the PV panels on the available area using the second scenario in which the tilt angle is 15°. It is clear that the PV panels are installed over two complete roofs and three separate small, distributed roofs in which the total area is less than the first scenario area.
2.3. Third Scenario

An additional solution has been suggested by the authors to accommodate the limited area of the roof buildings. The solution is based on using the optimal tilt angle of $22^\circ$ for the first string of the PV system and a tilt angle of $15^\circ$ for the other strings. The advantage of using this configuration is that it provides more energy than the second scenario and accommodates the limited area of the roof building without shading. Figure 6 shows the authors’ proposed configuration, which can be used over buildings’ roofs where the area is limited. Figure 7 shows the relationship between elevation angle and spacing between rows for all scenarios. It is clear that the distance between rows is increased by increasing the tilt angle. Therefore, the first scenario has the maximum spacing between rows.

Figure 5. Distribution of the panels in the second scenario.

Figure 6. The configuration of the third scenario.
Figure 7. Relationship between elevation angle and spacing between rows: (a) Scenario 1, (b) Scenario 2, (c) Scenario 3.
2.4. Estimating of Energy Production

This section presents the method of estimating the energy production of the PV systems by varying the tilt angle. In addition, a comparative study between the simulated energy output of the PV system and the measured ones is also presented in this section.

The energy produced by the PV system \( E \) depends on several parameters as suggested by [32]:

\[
E = A \times r \times G_R \times PR
\]  

(1)

where:
- \( A \) — Surface area.
- \( r \) — Solar panel efficiency.
- \( G_R \) — Tilted surface mean solar radiation.
- \( PR \) — Performance ratio.

The performance ratio used in this study is 0.798, according to the PVsol simulator for the system, while the average solar radiation for tilted surface, \( G_R \), is given by [33, 34]:

\[
G_R = (G - D)R_B + DR_D + G_d R_R
\]  

(2)

where \( G \) and \( D \) are ground and diffuse solar radiation in kWh/m\(^2\), respectively. The symbol \( \rho \) refers to the ground reflection, and the radiation coefficients \( R_P, R_D, \) and \( R_R \) are given by [35–39]:

\[
R_P = \frac{\cos(L - \beta) \cos \delta \cos \omega_{ss} + \sin(L - \beta) \sin \delta}{\cos L \cos \delta \cos \omega_{ss} + \sin L \sin \delta}
\]  

(3)

where \( L, \beta, \) and \( \omega_{ss} \) are location latitude, tilt angle, and hour angle, respectively. \( \delta \) is the declination angle and can be given by:

\[
\delta = 23.45 \sin \frac{360(284 + n)}{365}
\]  

(4)

where \( n \) is the number of days in the year. The reflected solar radiation \( R_R \) is calculated as:

\[
R_R = \frac{1 - \cos \beta}{2}
\]  

(5)

\[
R_D = \frac{1 + \cos \beta}{2}
\]  

(6)

By simulating and substituting the previous equations, the energy yield can be estimated for the intended location.

As mentioned before, the three scenarios would produce different amounts of energy even though the number of panels is the same. The energy production of the PV system varies during the year, in which the maximum energy production is in May and the lowest energy production is in December in both scenarios.

Figure 8 presents a comparison between the energy production for all scenarios. It can be noticed that the first scenario has the maximum energy production, followed by the third scenario. This is expected due to the higher tilt angle which exposes the panels to more solar energy than the second scenario. Furthermore, in the first and the third scenarios, the area of the panels exposed to the sunlight is greater than that in the second scenario. However, the second scenario has been installed by the designer due to the reasons mentioned before, while the third scenario is a new scenario suggested and presented in this paper.
Figure 8. Energy production for all scenarios on a monthly basis.

3. System Configuration

The connection diagram between the panels and the inverters is shown in Figure 8. The panels are connected in four main groups: $2 \times 17$, $6 \times 17$, $2 \times 15$, and $7 \times 17$. Each group has a specific number of strings, in which panels are connected in series.

Table 2 gives details about the selected tilt and elevation angles, the distances between the PV panels, and the total roof areas for all scenarios. Table 3 shows solar irradiance in kWh/m$^2$ at different inclination angles.

Table 2. Selected angles, distances, and the total roof areas for all scenarios.

| Angles and Distances | Scenario 1 | Scenario 2 | Scenario 3 |
|----------------------|------------|------------|------------|
| Tilt angle           | $22^\circ$ | $15^\circ$ | $22^\circ$ (First String)/$15^\circ$ (Others) |
| Elevation angle      | $27^\circ$ | $19.2^\circ$ | $19.2^\circ$ |
| Height difference (m)| 1.3        | 1.04       | 1.3 (First String)/1.04 (Others) |
| Model row spacing (m)| 1.73       | 1.42       | 1.42       |
| Total roof area (m$^2$)| 2267.8 | 1893.77  | 1893.77 |

In this section, the size of the PV system for the second scenario, which has been selected, is introduced. The number of needed PV panels and inverters and the appropriate approach of connections are discussed.

The required PV panels that met a demand of 300 kW are decided to be 790 modules of 380 W each. In addition, six inverters are needed to integrate the PV system with the grid [30,31]. The method of connecting the PV models with the inverters in the form of strings is shown in Figure 9. More details about the required system parameters and quantities are also shown in Table 4.
Table 3. Solar irradiance in (kWh/m$^2$) at different inclination angles.

| Month   | Inclination Angle (degree) | Solar irradiance (kWh/m$^2$) |
|---------|---------------------------|------------------------------|
| January | 60                        | 164                          |
| February| 60                        | 147                          |
| March   | 30                        | 189                          |
| April   | 30                        | 205                          |
| May     | 10                        | 241                          |
| June    | 10                        | 254                          |
| July    | 10                        | 262                          |
| August  | 10                        | 245                          |
| September | 30                         | 229                          |
| October | 30                        | 215                          |
| November| 60                        | 183                          |
| December| 60                        | 156                          |

Total energy 2490

Figure 9. Connection diagram between the panels and the inverters.

Table 4. Equipment sizing details.

| Case                          | Type or Quantity                  |
|-------------------------------|-----------------------------------|
| PV panel surface             | 2118 m$^2$                        |
| Dimensions of module         | 2000 mm × 991 mm × 40 mm           |
| Brand of PV modules          | JASOLAR                           |
| Model number                 | JAM72S03-380/PR                   |
| Rated maximum power of PV module (W) | 380                             |
| Type of cell                 | Mono                              |
| Number of PV modules         | 790                               |
| Brand of inverters           | Chint                             |
| Model number                 | CPS SCA50KTL-DO/400               |
| Rated AC output power (kW)   | 50                                |
| Number of inverters          | 6                                 |
| Installation type            | Rooftop                           |

The single-line diagram (SLD), shown in Figure 10, was drawn and sized according to the Ministry of Electricity standards of grid integration for the distribution system of low and medium voltages. Moving in detail to the SLD, the number of the connected solar panels is 790 panels distributed in an area of 2118 m$^2$. In addition, there are six inverters with a capacity of 50 kW each. The appropriate connection between these panels and
inverters is to establish three groups of series panels, 15, 16, and 17, each group connected with one of the inverters’ MPPTs. This distribution is determined by the inverters’ voltage limits, which keep the voltage up to 950 volts.

Moreover, the SLD represents the sizing of cables and their cross-sectional areas (CSAs) that connect the panels with the inverters. PV cables and AC cables that connect inverters with the grid are also presented in this diagram. Their cross-sectional areas are 6 mm² and 35 mm², respectively. From the main bus bar to the grid, cables of 185 mm² are used. A molded case circuit breaker (MCCB), with 122 A capacity, is connected between every inverter and the main bus bar. The main circuit breaker, which is established between the main bus bar and the low voltage grid, has a capacity of 500 A.

4. Comparison between Measured and Estimated Energy

Table 5 illustrates the estimated energy for the studied location considering the three different scenarios throughout the year. Nevertheless, the second scenario was established, and the measured energy for this scenario has been available since August 2019. Therefore, the comparison depends on the measured energy from August to December when the system was ready and successfully integrated with the grid. Table 6 gives information regarding the estimated average energy on a monthly basis. Generally, the estimated energy output is close to the measured output for the given period. The minimum value of the percentage error registered was in August, with a value of about 2.7%, while the maximum value appeared in November, about 18%.
Table 5. Monthly and annual estimated energy production of all scenarios in kWh.

| Month     | 22° Tilt Angle | 15° Tilt Angle | Configuration Proposed by the Author |
|-----------|----------------|----------------|--------------------------------------|
| January   | 42,863.72      | 40,586.62      | 41,346.98                            |
| February  | 43,120.12      | 42,701.92      | 41,905.32                            |
| March     | 51,605.42      | 50,982.12      | 51,189.88                            |
| April     | 48,698.62      | 49,404.42      | 49,169.15                            |
| May       | 48,710.22      | 50,453.52      | 49,872.42                            |
| June      | 46,055.82      | 48,218.22      | 47,497.42                            |
| July      | 47,434.52      | 49,388.12      | 48,736.92                            |
| August    | 47,504.22      | 49,234.62      | 48,657.95                            |
| September | 47,435.52      | 47,469.22      | 47,458.12                            |
| October   | 49,030.32      | 47,195.12      | 47,806.98                            |
| November  | 44,819.02      | 41,655.71      | 42,710.34                            |
| December  | 43,419.12      | 39,732.51      | 40,961.58                            |
| Annual energy production | 560,696.64 | 557,025.33 | 557,313.06 |

Table 6. Comparison between estimated and measured energy output of the PV system in kWh, with percentage error calculations.

| Estimated at 15° Tilt | Measured   | Percentage Error % |
|-----------------------|------------|---------------------|
| August                | 49,234.62  | 47,909.40           | 2.69                          |
| September             | 47,469.22  | 44,873.24           | 5.46                          |
| October               | 47,195.12  | 40,545.59           | 14.10                         |
| November              | 41,655.71  | 33,842.27           | 18.75                         |
| December              | 39,732.51  | 34,447.50           | 13.30                         |
| January 2020          | 40,586.62  | 35,971.36           | 11.37                         |

There are several circumstances for reducing the energy production of the PV system and therefore reducing the efficiency of the PV system. For instance, excessive heat, especially in KSA, and other nonanticipated weather conditions decrease the energy production of the system [40–46].

5. Conclusions

This paper proposed a new PV configuration over the buildings’ roofs for limited-area applications. The proposed configuration is based on selecting an optimum tilt angle for the first string of the PV system that generates the largest amount of energy. The other strings of the PV system, in this configuration, can be selected to prevent shading in the limited-area roofs. The proposed new configuration was simulated and tested with other scenarios. The first scenario used the optimal tilt angle for the whole PV system, which generates the maximum amount of electric energy. However, this scenario can only be used if the roof’s area is not limited, which is not a critical case. Knowing that, in the case of a roof area restriction, it is more efficient to change the tilt angle of the PV panels than to obtain the shading of the PV panel, as the amount of energy produced varies insignificantly. Therefore, the second scenario, which was applied to accommodate the limited roof area, produces lower energy than the proposed configuration.

The proposed configuration can be used routinely over buildings’ roofs where the roof area is limited to produce a larger amount of energy. In addition, this configuration can be applied for small-capacity PV systems as well. Nevertheless, the area saved for such systems will be very small, since the saved area per module for each tilt angle is very small. The authors recommend using the new configuration where roof area is limited to increase the energy output of the whole PV system, although some regulations regarding PV system installations in some countries prevent the use of such a configuration over the roof of a building for aesthetic reasons.
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