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Techno-economic assessment of application of solar PV in building sector: A case study from Saudi Arabia

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Abstract

Purpose – The Kingdom of Saudi Arabia (KSA) is facing a rapid growth in energy demand mainly because of factors like burgeoning population, economic growth, modernization and infrastructure development. It is estimated that between 2000 and 2017 the power consumption has increased from 120 to 315 TWh. The building sector has an important role in this respect as it accounts for around 80 percent of the total electricity consumption. The situation is imposing significant energy, environmental and economic challenges for the country. To tackle these problems and curtail its dependence on oil-based energy infrastructure, KSA is aiming to develop 9.5 GW of renewable energy projects by 2030. The campus of the King Fahd University of Petroleum and Minerals (KFUPM) has been considered as a case study. In the wake of recently announced net-metering policy, the purpose of this paper is to investigate the prospects of rooftop application of PV in buildings. ArcGIS and PVsyst software have been used to determine the rooftop area and undertake PV system modeling respectively. Performance of PV system has been investigated for both horizontal and tilted installations. The study also investigates the economic feasibility of the PV application with the help of various economic parameters such as benefit cost ratio, simple payback period (SPP) and equity payback periods. An environmental analysis has also been carried out with the help of RETScreen software to determine the savings in greenhouse gas emissions as a result of PV system.

Design/methodology/approach – This study examines the buildings of the university campus for utilizable rooftop areas for PV application. Various types of structural, architectural and utilities-related features affecting the use of building roofs for PV have been investigated to determine the corrected area. To optimize the performance of the PV system as well as space utilization, modeling has been carried out for both horizontal and tilted applications of panels. Detailed economic and environmental assessments of the rooftop PV systems have also been investigated in detail. Modern software tools such as PVsyst, ArcGIS and RETScreen have also been used for system design calculations.

Findings – Saudi Arabia is embarking on a massive solar energy program as it plans to have over 200 GW of installed capacity by 2030. With solar energy being the most abundant of the available renewable resource for the country, PV is going to be one of the main technologies in achieving the set targets. The country has, however, unlike global trends, traditionally overlooked the small-scale and building-related application of solar PV, focusing mainly on larger projects. This study explores the prospects of utilization of solar PV on building roofs. Building rooftops are constrained in terms of PV application owing to wide ranging obstacles that can be classified into five types – structural, services, accessibility, maintenance and others. The total building rooftop area in the study zone, calculated through ArcGIS has been found to be 857,408 m^2 of which 352,244 m^2 is being used as car parking and hence is not available for PV application. The available roof area, 505,165 m^2 is further hampered by construction and utilities related features including staircases, HVAC systems, skylights, water tanks and satellite dish antennas. Taking into account the relevant obstructive features, the net rooftop area covered by PV panels has been found to be in the range 25–41 percent depending upon the building typology, with residential buildings offering the least. To optimize both the system efficiency and space utilization, PV modeling has been carried out with the help of PVsyst software for both the tilted and horizontal installations. In terms of output, PV panels with tilt angle of 24° have been found to be 9 percent more efficient compared to the horizontally installed ones. Modeling results provide a net annual output 37,750 and 46,050 MWh from 21.44 and 28.51 MW of tilted and horizontal application of PV panels, sufficient to respectively meet 16 and 20 percent of the total campus electricity requirements. Findings of the economic analysis reveal the average SPP for horizontal and tilted applications of the PV to be 9.2 and 8.4 years, respectively. The benefit cost ratio for different types of buildings for horizontal and tilted application has been found to be ranging between 0.89 and 2.08 and 0.83 and 2.15, respectively. As electricity tariff in Saudi Arabia has been increased this year by as much

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as 45 percent and there are plans to remove $54bn of subsidy by 2020, the cost effectiveness of PV systems will be greatly helped. Application of PV in buildings can significantly improve their environmental performance as the findings of this study reveal that the annual greenhouse gas emission in the KFUPM campus can be reduced by as much as 40,199 tons carbon dioxide equivalent.

Originality/value – The PV application on building roof especially from economic perspective is an area which has not been addressed thus far. Khan *et al.* (2017) studied the power generation potential for PV application on residential buildings in KSA. Asif (2016) also investigated power output potential of PV system in different types of buildings. Dehwas *et al.* (2018) adopted a detailed approach to determine utilizability of PV on residential building roofs. None of these studies have covered the economics of PV systems. This study attempts to address the gap and contribute to the scholarship on the subject. It targets to determine the power output from different types of building in an urban environment by taking into account building roof conditions. It also provides detailed economic assessment of PV systems. Subsequent environmental savings are also calculated.

Keywords Environment, Sustainability, Saudi Arabia, Buildings, Solar energy, Solar PV

Paper type Research paper

1. Introduction

Over the last two decades renewable energy has made an important contribution to the energy equations both at national and international levels. There are a wide range of benefits renewable energy has on offer including diversity in supply mix, enhanced energy security through reduction in imports and environmental-friendly energy supply. Due to its favorable characteristics, in 2015, renewables experienced a greater capacity addition at the global level as compared to fossil fuel technologies. Renewable energy, contributing to more than 23 percent of the power generation, has globally attracted new investments of more than $333bn, double as compared to fossil fuel based technologies (Louw, 2018). Solar energy and wind power are the two renewable technologies leading the way. Solar photovoltaic (PV), a technology that converts solar radiation directly into electricity, is one of the most successful renewable technologies. Experiencing a yearly growth rate of almost 33 percent in 2016, its worldwide installed capacity reached at 303 GW (REN21, 2017).

Diversity in size is one of the key strengths of renewable energy systems which have made them reach out to a larger consumer base as compared to other forms of energy. Solar PV projects, for example, range from less than 100 Watts to hundreds of Mega Watt (MW). Small-scale systems have made a significant contribution toward the success of solar PV applications. There have been several types of policy incentives in place especially in developed countries to promote the small-scale application of renewable technologies including feed-in-tariff (FIT), renewable obligation certificate (ROC), net metering and renewable heat incentive. FIT, pioneered by Germany in 1990s, has been one of the most successful of these policies which is now being implemented in over 50 countries (Asif *et al.*, 2017).

The Kingdom of Saudi Arabia (KSA) holds one of the biggest shares of old and gas reserves at the global level. The country experiences escalating energy demand due to factors like population growth, infrastructural and economic developments and modernization (Ahmed *et al.*, 2017; Al Fardan *et al.*, 2017; Dehwah and Asif, 2017). Statistics indicate that between 2000 and 2017 the power consumption has increased from 120 to 315 TWh (ECRA, 2017). The rapid growth in energy demand has been mainly dictated by the building sector as it consumes around 80 percent of the total electricity consumption (Khan *et al.*, 2017). The residential buildings have the biggest share, accounting for over 50 percent of the total electricity produced in the country. To address the challenge of fast growing energy demand and diversify the supply mix that currently relies on oil and gas only, Saudi Arabia is embarking on energy conservation and renewable energy initiatives. Rich solar resource, with annual radiation level reaching over 2,200 kWh/m^2 is the cornerstone of KSA's renewable base (Asif, 2016a, b). Taking an enormous step on top of its target of developing 9.5 GW of renewables by 2030, earlier this year KSA has signed an understanding with the Softbank to develop 200 GW of solar energy project through 2030 (Wald, 2018).

Globally, the solar energy developments have been greatly supported by building-related applications. In KSA, however, these types of applications have been overlooked as traditionally large-scale projects have been the point of interest. Small-scale and building-related applications of PV need to be paid attention. In this respect the Electricity and Cogeneration Regulatory Authority has announced a net-metering policy in 2017 to support solar PV systems up to 2 MW of installed capacity (Bellini, 2017; Parnell, 2017). While the details of the net-metering policy are being worked out, it is important to mature technical details on the potential and utilization of PV. There has been significant body of research scholarship on application of PV in buildings in other countries. Assessment of rooftop PV systems in buildings has been undertaken by many researchers across the world (Gautam *et al.*, 2015; Hong *et al.*, 2014; Karteris *et al.*, 2013; Khan and Arsalan, 2016). The effect of building-integrated PV on heat gain through envelope has also been considered in several studies (Ban-Weiss *et al.*, 2013; Zhang *et al.*, 2017). The impact of rooftop application of PV in terms of cooling load reduction has also been studied in various countries, i.e. the USA (Dominguez *et al.*, 2011), Greece (Kapsalis *et al.*, 2014) and China (Wang *et al.*, 2017). There is a limited scholarship on the subject of use of PV in KSA building sector. The PV application on building roof especially from economic perspective is an area which has not been addressed thus far. Khan *et al.* (2017) studied the power generation potential for PV application on residential buildings in KSA. Asif (2016a, b) also investigated power output potential of PV system in different types of buildings. Dehwah *et al.* (2018) adopted a detailed approach to determine utilizability of PV on residential building roofs. None of these studies have covered the economics of PV systems. This study is to address the gap and contribute to the scholarship on the subject. It aims to determine the utilizability of different types of building roofs for PV application in a typical urban setting of KSA. It also plans to undertake detailed economic assessment of PV application on building rooftops considering both tilted and horizontal installations.

King Fahd University of Petroleum and Minerals (KFUPM) has been considered as case study in this study since its diverse and large building infrastructure, size of population and utility requirements resemble with that of an urban-scale environment. It examines the buildings of the university campus for utilizable rooftop areas for PV application. Various types of structural, architectural and utilities-related features affecting the use of building roofs for PV have been investigated to determine the corrected area. To optimize the performance of the PV system as well as space utilization, modeling has been carried out for both horizontal and tilted applications of panels. Detailed economic and environmental assessments of the rooftop PV systems have also been investigated in detail. Modern software tools such as PVsyst, ArcGIS and RETScreen have also been used for system design calculations.

2. Methodology

Saudi Arabia is one of the largest countries in the Middle East with an area of 2.3 million km^2 with land elevation varying from 0 to 3,000 m above the mean sea level (Asif, 2016a, b) and a total area of 2,149,690 km^2. The climatic conditions in the country are predominantly hot and dry. It lies between 32°N and 17°N latitude and 56°E and 28°E longitude (Asif, 2016b). The KFUPM is located in the city of Dhahran. This study has selected the KFUPM campus as the study area since in terms of number of its large area, inhabitants, size of infrastructure and scale of utilities requirements, it has resemblance to a city and thus serves the scope of this study. It, for example, has a significant diversity in building types which include academic and admin blocks, residences for faculty and staff, student halls of residences, recreational centers, schools, sports facilities, shopping malls, medical centers, workshops, warehouses and restaurants. These different types of buildings can have a further categorization. Residential buildings, for example, have a wide variation in size, ranging from studio and one-bed room flats to over five-bedroom villas.

The KFUPM campus, like the rest of the country, is facing a rising trend in energy consumption. The student numbers are gradually increasing in the university leading to growth in teaching and research facilities and support infrastructure. Consequently the energy consumption has increased from 175,242 MWh in 2003 to 258,670 MWh in 2016 as shown in Table I.

The range of activities in this study includes solar resource assessment, rooftop area assessment, calculation of PV, PV system modeling and economic and environmental assessment as highlighted in Figure 1. Buildings in KSA typically have flat roof. Also, there are pretty consistent trends in terms of building height. The situation offers a degree of freedom in terms of tilt angle and orientation. The study has therefore considered the common installation choice. During the simulation process other installation positions both in terms of orientation and inclination were also tried but eventually the optimum were used in the analysis.

Year	Number of students	Electricity use (MWh)
2003	8,755	175,240
2006	8,471	185,410
2009	9,080	208,625
2012	9,100	219,935
2016	9,486	258,670

Table I. Growth trend in annual electricity requirements of KFUPM

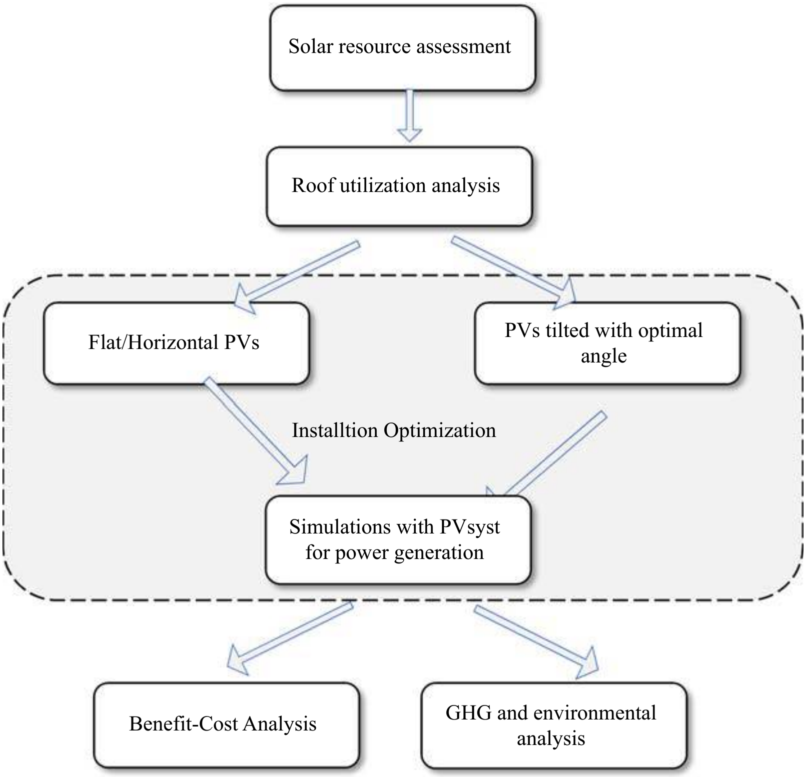

Figure 1. Methodology of the study

3. PV system design and modeling

The PV system design in this study has been categorized in four main stages: solar resource assessment, PV utilizable rooftop area calculation, system components and modeling.

3.1 Solar resource assessment

Geographically, KSA is well positioned for harnessing solar energy. The country exhibits an annual average solar radiation level of over 6 kWh/m^2/day (Alnaser and Alnaser, 2011). Annually, clear sky days are in a range of 80–90 percent with solar radiation level reaching over 2,400 kWh/m^2 as can be seen in Figure 2 (Khan *et al.*, 2017). The site in this study, KFUPM, is located in the city of Dhahran in the Eastern Province of Saudi Arabia. With geographic coordinates of 26°18'29" North, and 50°9'1" East, Dhahran has an annual solar radiation level of around 2,100 kWh/m^2. Monthly distribution of solar radiation is provided in Table II. Figure 3 provides sun path diagram for the KFUPM. Sun path diagram is very useful that can help estimate the impact of shading on PV systems. In this study given the large number of buildings, largely of similar design and height, the impact of shadowing has been considered as negligible.

3.2 PV utilizable rooftop area calculation

3.2.1 Roof area. This study investigates the scope of building rooftops for PV application. Calculation of the available roof area is therefore one of the main design requirements. The buildings in KFUPM have been categorized into seven main types: academic buildings, car parking, faculty housing, community centers, staff housing, sports centers and student housing.

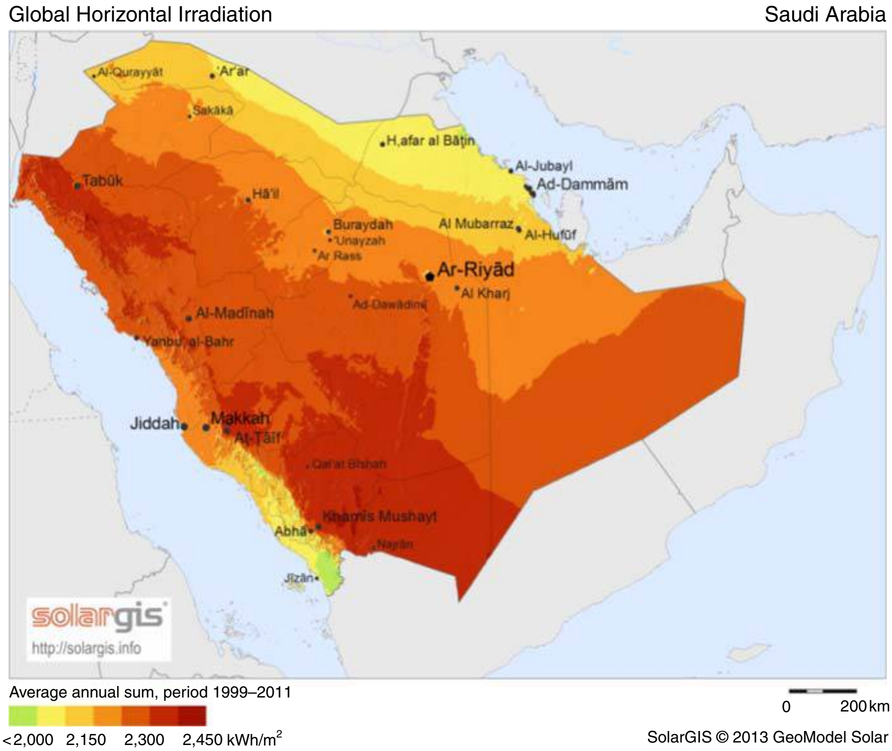

Figure 2.
Solar map of Saudi Arabia

Month	Hh (Wh/m^2)	H_{opt} (Wh/m^2)
January	3,880	5,090
February	4,800	5,830
March	6,070	6,730
April	6,600	6,670
May	7,790	7,340
June	8,320	7,520
July	7,860	7,270
August	7,440	7,310
September	6,910	7,450
October	5,750	6,870
November	4,170	5,320
December	3,730	5,040
Monthly average	6,110	6,537

Notes: Hh, irradiance on horizontal plane; $H_{opt.}$, irradiance on optimally inclined plane

Table II.
Daily solar irradiance level for Dhahran

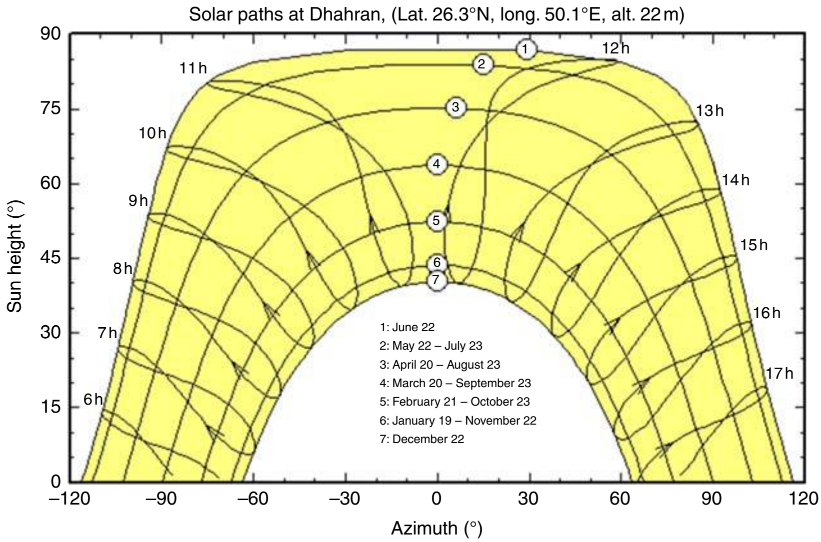

Figure 3.
Sun path diagram for Dhahran

These buildings are generally situated in clusters in the campus. Areas of building rooftops as presented in Table III have been determined employing ArcGIS software.

Roofs of the car parking buildings are also used for parking, therefore, becoming unutilizable for PV use. Due to their unavailability for application of PV, the car parking rooftop area has been excluded from calculations from here onwards.

3.2.2 PV utilizable area. In recent years, application of solar PV in buildings has recorded a steep growth around the world (Khan *et al.*, 2017; Asif, 2016a, b). PV can be used in buildings on roof as well as on façade. Utilization of buildings for PV is usually expressed in terms of utilization factor (UF), defined as the ratio of the available area for PV utilization to the total roof area. The UF of building roof for PV may vary significantly from one place to another due to wide ranging design, construction and cultural features. Investigation of building rooftops for PV use has been an area yet to be explored in KSA. Building rooftops in Saudi Arabia are usually heavily occupied as can be seen in Plate 1 that compares a typical Saudi neighborhood with that of Western Europe. There is a lack of regulation in KSA about the building rooftops (Dehwah and Asif, 2018). Building roofs are therefore typically populated with wide ranging architectural and structural, and services-related features that pose restrictions toward PV application both in terms of space-availability and shading. Furthermore, inter-row spacing is needed for manual cleaning of dust even in case of horizontal application of PV panels. Typical restrictions can be categorized into five types – structural, services, accessibility, maintenance and others – as described in Table IV. These obstacles have a massive impact on the utilizability of roofs for PV applications.

PV panels cannot be applied to cover all of the available roof area due to obstructions posed by various structural and services-related features as well as to accommodate for the spacing required for shadow adjustment. Typical potentially obstructive features on building rooftops include staircases, balustrade walls, skylights, HVAC systems, satellite antennas, water tanks and openings for mechanical and plumbing installations. When it comes to roof construction, buildings in KFUPM have flat roof with negligible balustrade walls. The area that can be utilized for PV application is therefore calculated considering all concerned obstacles. Sample buildings from each category were examined more closely to determine the proportion of rooftop area useable for PV application taking into account the relevant corrective factors. This exercise has been undertaken by digitizing the buildings using AutoCAD software with the help of aerial photos taken from Google maps.

The output from a PV system is considerably influenced by the orientation and inclination angle of the installed panels. While a south-facing orientation can be maintained, the optimum tilt angle varies on monthly basis as highlighted in Table II. To make the most of the available solar resource, a single- or double-axis solar tracking system can be employed. It however results into additional cost and maintenance issues. PV systems in buildings are therefore mostly installed at fixed angles. The optimum tilt angle for Dhahran for fixed installation as determined through literature review is 24° (Duffie and Beckman, 2013).

Table III.
Estimation of building roof areas

Building type	Roof area (m^2)
Car parking	352,244
Faculty housing	157,153
Support facilities	130,711
Academic buildings	97,232
Student housing	91,300
Staff housing	17,340
Community centers	11,430
Total area	857,408

(a) (b)

Plate 1.
Comparison of typical residential building rooftops in Europe and KSA

Notes: (a) German neighborhood; (b) Saudi neighborhood

This study investigates the power generation potential from PV considering horizontal installation as well as at the optimum tilt angle. It is noteworthy, as can also be seen from Table II that the solar yield is higher at the tilted installation as compared to horizontal installation. However, the tilted application of PV panels has a downside in terms of space utilization – PV panels cast shadow on the panels behind. To avoid overshadowing from PV panels, an appropriate space between successive rows needs to be maintained which depends upon the site coordinates as well as height of the panel. Space is also needed for cleaning and maintenance requirements. The conceptual layout of tilted and horizontal layout of PV panels is highlighted in Figure 4.

The utilizability of rooftops for solar PV varies with the type of building. The UF – ratio of the available area for PV utilization to the total roof area – has been found to range between 25 and 41 percent (as shown in Table V) with faculty residential buildings turning out to be the least effective due to greater degree of obstructive features on rooftops.

3.3 System modeling

The PV panels used in the study are of 250Wp mono crystalline type. Subsequent balance of system components including PV array circuit combiner, fuse switches, inverters,

Classification	Components
Structural restrictions	Parapet walls Annexes Atrium shafts Staircase, columns Rebars Roof geometry
Service restrictions	Water tanks AC package units Dish antennas Atrium shaft area AC condensers Water boilers
Accessibility restrictions	Nearby access 1 m adjacent to walls Inter-row spacing
Shading restrictions	Impact of height from Parapet walls Annexes Atrium shafts walls Staircase Service components
Other restrictions	Courtyard Clothesline

Table IV. Classification of main restrictions

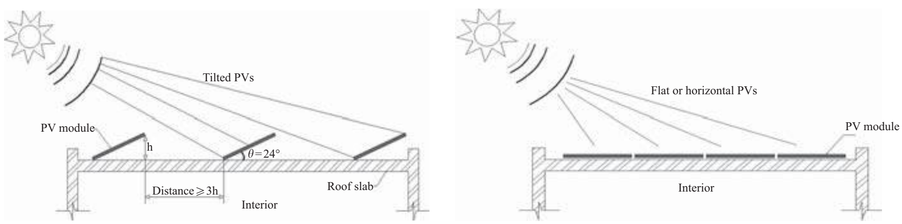

Figure 4. Horizontal and tilted applications of PV panels

cables and racking have been used. PVsyst software has been used to calculate the system output for both the horizontal and tilted applications. Some of the key specimen details of the PV output modeling carried out with PVsyst are discussed here. As specimen example, the findings of the system modeling for tilted application of PV panels on academic buildings are provided. Values for the nominal power for tilted PV application on academic buildings have been furnished in Figure 5. It can be observed that although the power output is greater in summer months, the losses are also higher. These losses are termed as collection losses and are due to factors like irradiance fluctuation, temperature variations, cell mismatch, module quality and wiring, etc. These losses have been found to be higher in summer months mainly due to higher ambient temperature which can cross 50°C.

Monthly performance ratio of PV system is highlighted in Figure 6. The performance ratio (P_R) is an indicator of the quality of the system itself, independently of the incoming irradiance.

Table V. Area utilization for horizontal and tilted installation of PV panels

Building type	Total roof area (m^2)	Horizontal installation Utilization factor (%)	Horizontal installation Net PV utilized area (m^2)	Tilted (24°) installation Utilization factor (%)	Tilted (24°) installation Net PV utilized area (m^2)
Faculty housing	157,153	37	58,147	25	39,288
Support facilities	130,711	54	70,584	39	50,977
Academic buildings	97,232	51	49,588	40	38,893
Student housing	91,299	47	42,911	34	31,042
Staff housing	17,338	50	8,669	41	7,109
Community centers	11,432	46	5,259	35	4,001
Total	505,165		235,157		171,310

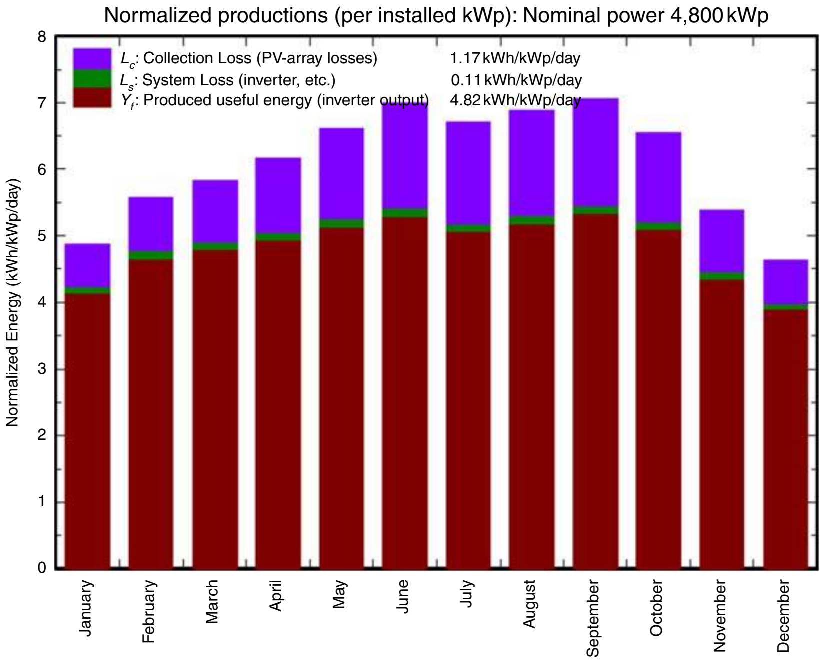

Figure 5. Normalized production values from academic buildings

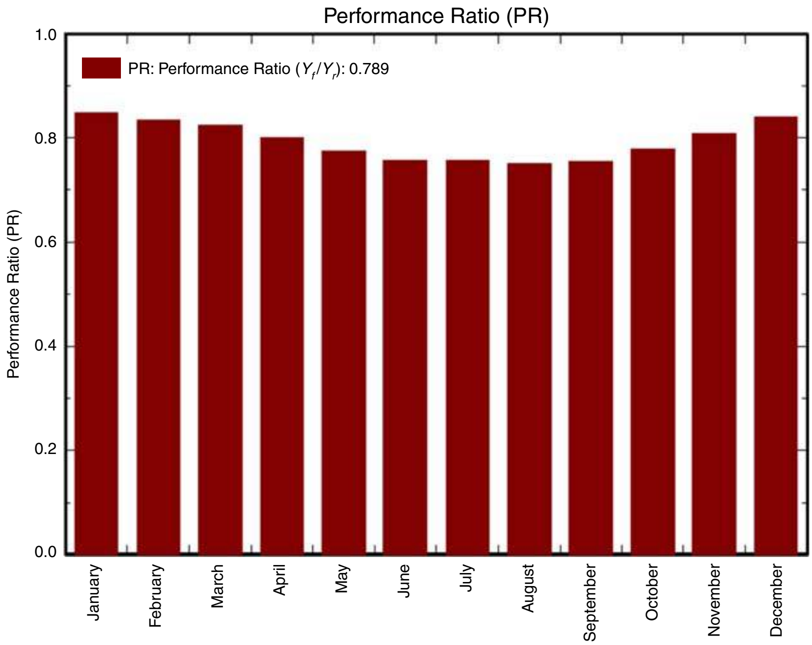

Figure 6.
Performance ratio of PV systems for academic buildings

However, it is given by $P_R = (Y_f/Y_r)$ (Mermoud and Wittmer, 2014); where P_R is the performance ratio of the system; Y_f the final system yield energy to the grid; Y_r the reference yield energy production if the system were always running at nominal efficiency at standard test conditions (STC); and STC is the standard test condition for the for PV modules (irradiance: 1,000 W/m^2, module temperature: 25°C, air mass = 1.5).

The performance ratio of PV system has been found to have slight variation throughout the year. It is low in summer months, mainly due to higher ambient temperature resulting into more losses.

An overview of key parameters of the tilted PV system on academic buildings has been provided in Table VI. A flow diagram of the energy production from PV systems on these buildings has been provided in Figure 7, also describing the relevant losses at various stages.

The simulation results indicate that the tilted PV panels can deliver 9 percent more output compared to the horizontally installed ones. The total installed capacity of PV panels on KFUPM buildings is found to be 21.44 and 28.51 MW, respectively, for tilted and horizontal installations. It is noteworthy that tilted installation of PV panels requires

Parameter	Value
No. of PV modules	19,250
PV Pnom	4,800 kWp
No. of inverters	385
Inverters capacity	4,608 kW AC
Annual energy production	8,450 MWh
Annual specific production	1,760 kWh/kWp
Performance ratio	80%

Table VI.
Overview of results from academic buildings

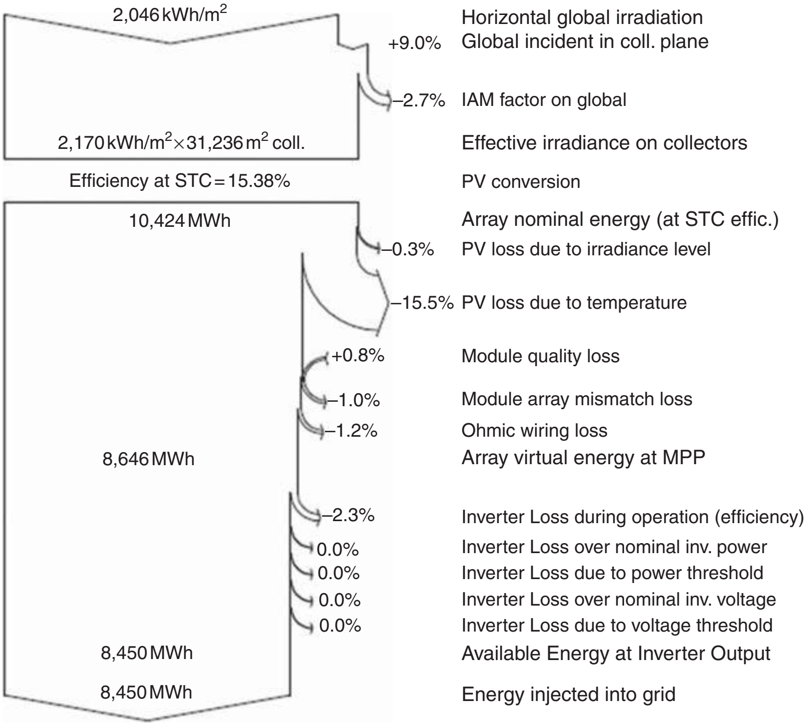

Figure 7. Typical system losses diagram

greater inter-row spacing. The simulation suggested that the total generation from PV systems installed over KFUPM building rooftops is expected to be 37,746 and 46,047 MWh for tilted and horizontal applications, respectively, sufficient to meet 16 and 20 percent of the total campus electricity requirements as described in Table VII.

Table VII. Summary results of KFUPM's generated energy from rooftop PV panels

Buildings type	Produced energy (MWh/year)	Benefit or cost of produced energy ($/year)	Contribution to KFUPM's power requirements (%)
Tilted application			
Faculty housing	8,871	614,938	3.9
Support facilities	11,223	777,978	4.9
Academic buildings	8,450	585,754	3.7
Student housing	6,733	466,732	2.9
Staff housing	1,571	108,902	0.7
Community centers	897.9	62,242	0.4
Total	37,746	2,616,553	16.4
Horizontal application			
Faculty housing	11,672	809,103	5.1
Support facilities	13,730	951,764	6.0
Academic buildings	9,693	671,919	4.2
Student housing	8,238	571,058	3.6
Staff housing	1,680	116,458	0.7
Community centers	1,034	71,677	0.4
Total	46,047	3,191,978	20.0

4. Economic analysis

A detailed economic analysis of the PV systems has been carried out employing multiple techniques including benefit cost analysis, simple payback analysis and equity payback analysis. The initial cost of the system including the price of PV panels and auxiliary components such as charge controller, inverters and cable besides the installation cost has been estimated as show in Table VIII. The prices for PV system components have been obtained through quotations from local suppliers and have been verified with international market prices.

Energy prices in KSA have seen a several-fold jump in the last couple of years. The electricity tariff has also been revised. The tariff currently applicable to government buildings is SAR 0.32/kWh (UScent 8.5/kWh). The project life cycle has been considered to be 25 years. PV panels are assumed to last this period as PV industry standard is to provide 25–30 years of warranty. Inverters are assumed to be replaced every eight years. The cost of inverters is regarded to have a discount rate of 4 percent per year. The cost of replacing invertors is translated to the net present value, and is then distributed to annual operational costs. These costs are added to the original O&M costs. Figures 8 and 9 show cash flow diagrams for the rooftop PV systems and the results of the benefit cost ratio analysis are provided in Table IX.

Simple payback period (SPP) and equity payback period analyses have also been undertaken with the help of cash flows developed by the RETScreen software. The results of benefit cost ration, SPP and equity payback period analyses have been provided in Table X. It can be observed that the average SPP for the horizontal and tilted applications of the PV system has been found to be 9.2 and 8.4 years, respectively (excluding community centers which showed neither SPP nor equity periods in all cases). The average equity periods for the two types of installations have been found to be 8.3 and 7.7 years.

5. Environmental analysis

An environmental analysis of the PV systems has been undertaken in the form of consequent reduction in greenhouse gas emissions. RETScreen software has been used to calculate the savings in emissions of three main gases: carbon dioxide, methane and nitrous oxide. For Saudi Arabia's electricity generation mix consisting of 55 percent oil and 45 percent gas, emission factors for the three gases have been found to be 0.816 Metric tons/MWh, 0.02678 kg/MWh and 0.00487 kg/MWh, respectively. The total avoided emissions have also been calculated in terms of carbon dioxide equivalent (CO_2e) as shown in Table XI.

6. Results and discussion

The key results of this study can be categorized under four areas: rooftop area calculation, PV power generation, economics of PV system and environmental analysis of PV system. The buildings in KFUPM campus can be categorized into seven broader types: academic buildings, car parking, community centers, faculty housing, staff housing, student housing and support facilities. Here support facilities cover sports centers, schools, shopping centers, medical clinic and restaurants while academic buildings include teaching blocks, laboratories and admin blocks. The findings of the rooftop area analysis reveal that the net available roof area on all buildings is 857,408 m^2. The car parking buildings having total roof area of 352,244 m^2 cannot be used for PV application as their rooftops are also used as parking space. The roof area potentially available for PV use is therefore estimated to be 505,165 m^2. However, this area needs to be further refined to take into account the construction and utilities related features causing obstruction toward the use of PV. The building sector in KSA has traditionally suffered from lack of regulations. Building rooftops are also unregulated in terms of architectural, structural and utilities features (Dehwah and Asif, 2018). A unique problem with residential buildings when it comes to use of PV systems is 6–7 feet high parapet walls.

Table VIII.
Initial investment calculation

	Number of modules (PVs)	Cost of modules ($) given ($150/PV)	Cost of support/integration ($30/module)	Number of inverters	Cost of inverters ($) given ($2,700/inverter)	Cost of setting/wiring given ($4/module)	Other costs (conveyor, etc.)($)	Cost of 5 unskilled workers for two months ($)	Cost of engineering and technicians for two months ($)	Total miscellaneous cost ($)	Gross initial investment ($)
PV tilted 24°											
Faculty housing	20,160	3,024,000	604,800	388	1,047,600	80,640	12,000	3,000	20,000	35,000	4,312,836
Support facilities	25,500	3,825,000	765,000	503	1,358,100	102,000	12,000	3,000	20,000	35,000	5,476,590
Academic buildings	19,200	2,880,000	576,000	384	1,036,800	76,800	12,000	3,000	20,000	35,000	4,144,140
Student housing	15,300	2,295,000	459,000	306	826,200	61,200	12,000	3,000	20,000	35,000	3,308,760
Labor and staff housing	3,570	535,500	107,100	71	191,700	14,280	12,000	3,000	10,000	25,000	786,222
Mosques	2,040	306,000	61,200	40	108,000	8,160	12,000	3,000	10,000	25,000	457,524
Flat horizontal PV											
Faculty housing	28,900	4,335,000	867,000	573	1,547,100	115,600	12,000	3,000	20,000	35,000	6,209,730
Support facilities	34,000	5,100,000	1,020,000	696	1,879,200	136,000	12,000	3,000	20,000	35,000	7,353,180
Academic buildings	24,000	3,600,000	720,000	489	1,320,300	96,000	12,000	3,000	20,000	35,000	5,194,170
Student housing	20,400	3,060,000	612,000	423	1,142,100	81,600	12,000	3,000	20,000	35,000	4,437,630
Labor and staff housing	4,160	624,000	124,800	86	232,200	16,640	12,000	3,000	10,000	25,000	920,376
Mosques	2,560	384,000	76,800	52	140,400	10,240	12,000	3,000	10,000	25,000	572,796

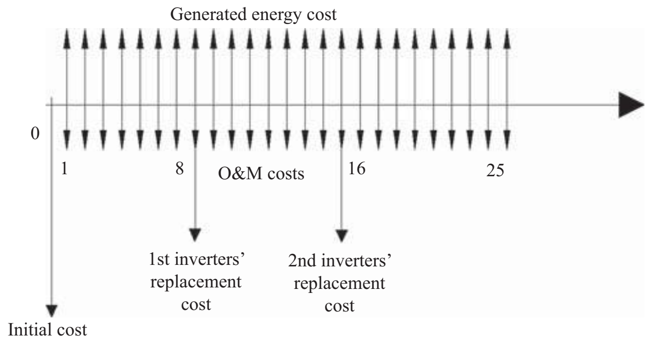

Figure 8.
Typical cash flow diagram the rooftop PV systems

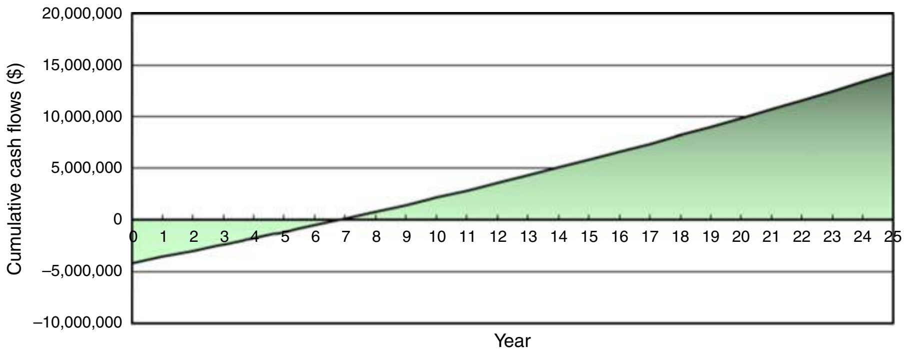

Figure 9.
Cash flow diagram for academic buildings (tilted PV panels)

	Produced energy (MWh/year)	Benefit or cost of produced energy ($/year)	Annual cost ($/year)	Benefit/cost ratio (BCR), annual
PV tilted 24°				
Faculty housing	8,871	756,962	374,234	2.02
Support facilities	11,223	957,659	445,902	2.15
Academic buildings	8,450	721,039	365,174	1.97
Student housing	6,733	574,527	314,206	1.83
Labor and staff housing	1,571	134,053	112,365	1.19
Mosques	897.9	76,618	92,278	0.83
Flat horizontal PV				
Faculty housing	11,672	995,972	490,795	2.03
Support facilities	13,730	1,171,581	562,262	2.08
Academic buildings	9,693	827,104	429,968	1.92
Student housing	8,238	702,949	384,297	1.83
Labor and staff housing	1,680	143,354	120,800	1.19
Mosques	1,034	88,231	99,432	0.89

Table IX.
Benefit to cost ratio calculation

These walls pose a significant constraint in terms of their shading impact. Besides, high parapet walls roofs are typically crowded with features like different architectural and geometric designs, staircases, annexes, rebars, air conditioners, satellite dish antennas, water storage tanks and water heating boilers. In some cases roofs are also used as courtyard.

All these hurdles limit the utilization of roofs for PV application. Furthermore, inter-row spacing is needed for routine manual cleaning of dust and other maintenance issues. These restrictions can be broadly categorized into five types – structural, services, accessibility, maintenance and others. However, the obstacles observed on KFUPM building roofs include: staircases, skylights, HVAC systems, satellite dish antennas and water tanks. The net area utilization by PV panels depends upon a number of other parameters including the installation layout, orientation and tilt angle, space requirement for shadow avoidance and maintenance and cleaning requirements. Since the output from PV systems is affected by the tilt angle of panels, this study considers horizontal as well as tilted installation of panels at the optimum angle of 24°. Taking into account the relevant obstructive features, the net area being covered by tilted and horizontally installed PV pales has been figured out to be, respectively, 171,310 and 235,157 m^2. It is therefore found that, though tilted installation of PV panels is comparatively more efficient, their horizontal positioning enables larger roof area to be capitalized thus leading to larger power output from the available rooftop areas.

The findings of the modeling work carried out using PVsyst to determine the power generation from PV system reveal annual output figures of 37,750 MWh (with installed cost of $24,687,882) and 46,050 MWh (with installed cost of $18,486,072), respectively, through tilted and horizontal application of panels. These can meet 16 and 20 percent of the total

Table X. Summary of SPP and equity periods for the investment

Area category	PV tilted 24° SPP (years)	PV tilted 24° Equity period (years)	PV tilted 24° BCR	Flat horizontal PV SPP (years)	Flat horizontal PV Equity period (years)	Flat horizontal PV BCR
Academic buildings	7.3	6.8	1.97	8.1	7.4	1.92
Faculty housing	7.2	6.7	2.02	7.8	7.2	2.03
Labor and staff housing	12.8	11.3	1.19	13.9	12.2	1.19
Mosques	na = 61.8	na	0.83	na = 35.8	na	0.89
Student housing	7.7	7.1	1.83	8.4	7.7	1.83
Support facilities	7.0	6.5	2.15	7.7	7.1	2.08
Average	8.4	7.7	1.67	9.2	8.3	1.66

Table XI. Analysis of greenhouse gas emissions

Buildings type	Emission inventory: Carbon dioxide (metric tons)	Methane (metric tons)	Nitrous oxide (metric tons)	Overall emission reductions (metric tons CO_2e)
Tilted application				
Faculty housing	7,239	0.238	0.043	7,744
Support facilities	9,158	0.301	0.055	9,798
Academic buildings	6,895	0.226	0.041	7,377
Student housing	5,494	0.180	0.033	5,878
Staff housing	1,282	0.42	0.008	1,371
Community centers	733	0.24	0.004	784
Total	30,801	1.011	0.184	32,952
Horizontal application				
Faculty housing	9,524	0.313	0.057	10,190
Support facilities	11,204	0.368	0.067	11,986
Academic buildings	7,909	0.260	0.047	8,462
Student housing	6,722	0.221	0.040	7,192
Staff housing	1,371	0.045	0.008	1,467
Community centers	844	0.028	0.005	903
Total	37,574	1,235	0.224	40,200

electricity needs of KFUPM. While power output is observed to be greater in summer months due to more sunshine hours, losses are also higher as ambient temperature soars, sometimes crossing 50°C.

KSA is a leading country in the world with regard to per capita energy consumption and CO_2 emissions. It is experiencing a rapid growth in energy demand and it is projected that by 2040, the national annual electricity requirements are likely to increase from the present figure of around 285 TWh to nearly 850 TWh. The power generation capacity by the time is projected to grow as much as 185,000 MW, demanding an addition of 4,200 MW/year. The consumption of oil and gas, the two sources for power generation, is projected to rise from present figure of around 110–425 million ton of oil equivalent. A trend of such a steep rise in energy demand is set to have huge implications for the country not only in terms of its energy scenario but also the environmental and financial outlook since export of petroleum fuels is the key foundation of country's revenues. Another critical challenge is to control the fast growing peak power demand. The situation advocates for a paradigm change in the patterns of generation and consumption of energy. Application of PV systems therefore can make a sizable contribution toward making buildings reduce the load on the national grid and increase the sustainability levels in the energy and building sectors.

The results of the environmental analysis reveal that the tilted and horizontal applications of PV respectively save annual emission of 32,952 tons CO_2 and 40,199 tons CO_2e. Solar PV systems can help improve the sustainability standards in buildings through reducing the greenhouse gas emission.

Findings of the economic analysis reveal the SPP for the horizontal and tilted applications of the PV to be 9.2 and 8.4 years, respectively. The benefit cost ration for different types of buildings for horizontal and tilted applications has been found to be ranging between 0.89 and 2.08 and 0.83 and 2.15, respectively. Saudi Arabia has traditionally had heavily subsidized energy prices including electricity tariffs (Alrashed and Asif, 2012, 2014, 2015). The situation is however changing with energy prices going through a phase of rationalization. The year 2016 saw a major jump in energy prices with electricity tariffs increased by up to 45 percent, recording a first change in 15 years (*Arab News*, 2016). Electricity prices are being widely forecasted to experience further hikes in coming years since according to the Kingdom's National Transformation Plan by 2020 subsidies on utilities have to be curtailed by over $54bn (200bn Saudi Riyals) (*The National*, 2016; Asif, 2016a; Mahmoud *et al.*, 2017). The trend of increase in electricity tariff structure is set to significantly improve the financial viability of PV systems.

Saudi Arabia is planning to embark on a massive renewable energy program as highlighted in its Vision 2030 (Pothecary, 2016). Solar PV is set to play the predominant role in meeting renewable targets. The country started solar PV projects as early as 1981 but is yet to make any meaningful use of the technology (Huraib *et al.*, 1996). There have been a few solar PV projects in recent years but at multi-MW scale. Traditionally, however, attention has been paid to large-scale projects while small-scale applications especially in buildings have been overlooked (DSSA, n.d.). Utilization of buildings for PV application is an important area that needs to be taken into account through effective policy framework and implementation plans. The global success of PV in recent years has been significantly helped not only by economy of scale and technological advancements but also conducive policies especially net-metering and FIT. Germany owing to strong FIT-driven applications in buildings has become a global leader in terms of solar PV installed capacity. Net-metering and FIT policies are being used in more than 50 countries (Ismail *et al.*, 2015). It would be helpful for Saudi Arabia to learn lessons from the success of PV programs in other countries and to develop proactive policies to motivate build sector stakeholders to adopt PV systems. Furthermore, incentives for consumers, obligatory policies for utilities such as ROC can also be useful.

7. Conclusions

Saudi Arabia is embarking on a massive solar energy program as it plans to have over 200 GW of installed capacity by 2030. With solar energy being the most abundant of the available renewable resource the country, PV is going to be one of the main technologies in achieving the set targets. The country has, however, unlike global trends, traditionally overlooked the small-scale and building-related application of solar PV, focusing mainly on larger projects. This study explores the prospects of utilization of solar PV on building roofs. Building rooftops are constrained in terms of PV application owing to wide ranging obstacles that can be classified into five types – structural, services, accessibility, maintenance and others. The total building rooftop area in the study zone, calculated through ArcGIS, has been found to be 857,408 m^2 of which 352,244 m^2 is being used as car parking and hence is not available for PV application. The available roof area, 505,165 m^2 is further hampered by construction and utilities related features including staircases, HVAC systems, skylights, water tanks and satellite dish antennas. Taking into account the relevant obstructive features, the net rooftop area covered by PV panels has been found to be in the range 25–41 percent depending upon the building typology, with residential buildings offering the least. To optimize both the system efficiency and space utilization, PV modeling has been carried out with the help of PVsyst software for both the tilted and horizontal installations. In terms of output, PV panels with tilt angle of 24° have been found to be 9 percent more efficient compared to the horizontally installed ones. Modeling results provide a net annual output 37,750 and 46,050 MWh from 21.44 and 28.51 MW of tilted and horizontal applications of PV panels, sufficient to respectively meet 16 and 20 percent of the total campus electricity requirements. Findings of the economic analysis reveal the average SPP for horizontal and tilted applications of the PV to be 9.2 and 8.4 years, respectively. The benefit cost ratio for different types of buildings for horizontal and tilted applications has been found to be ranging between 0.89 and 2.08 and 0.83 and 2.15, respectively. As electricity tariff in Saudi Arabia has been increased this year by as much as 45 percent and there are plans to remove $54bn of subsidy by 2020, the cost effectiveness of PV systems will be greatly helped. Application of PV in buildings can significantly improve their environmental performance as the findings of this study reveal that the annual greenhouse gas emission in the KFUPM campus can be reduced by as much as 40,199 tons CO_2e.

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