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Research Article

Design and Optimization of Solar Carport Canopies for Maximum Power Generation and Efficiency at Bahawalpur

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In recent years, the upturn demand of electricity and the generation of electrical power demand from fossil fuels are increasing day by day which results in environmental impacts on the atmosphere by greenhouse gases, and a high cost of electric power from these sources makes it unaffordable. The use of renewable energy sources can overcome this problem. Therefore, in this work, we present a solution by implementing the solar car parking lots. A detailed work has been done for solar car parking site selection and maximum solar electric power generation and its capacity effects with the shading of nearby trees and buildings by using the HelioScope online software developed by Folsom Labs. A detailed optimization and selection of car parking canopies are performed at different standard tilt angles to produce maximum solar photovoltaic energy, and it is analyzed that the monopitch canopy is the best to mount at solar car parking lots at a tilt angle of 10°. We have done a detailed economic analysis which shows that 14% electricity cost was offset by the installation of a solar car parking lot with 17% reduction in annual energy consumption from the grid at the proposed site. The total investment cost of the parking structure and the photovoltaic (PV) system can be paid back in 6-7 years.

1. Introduction

The ever-rising population of the world and mass urbanization in developing and developed countries have been two of the major challenges to the power sectors. In 2050, the world's population will reach up to 9.7 billion [1]. Pakistan will be among the top nine populous countries, which will contribute to a larger portion of such increased population. So far, hydroelectric power is the only major source of power generation along with the fossil fuel thermal power as an alternate source. There is a need to look towards sustainable and environment-friendly energy sources to cater to the future electrical power demand by 2050.

Renewable energy sources such as geothermal heat, tide, wind, and sunlight can be available in large amounts in nature, and they can easily cope with the increased electrical energy demand. The sun delivers 174000 TW electric power in the form of solar radiation to the upper level of the Earth's atmosphere which is reduced to 121800 TW at the Earth's surface level [2, 3]. This power is almost equal to one year usage of all human activities on Earth. Solar irradiance, which is the measure of solar power for a certain area, is 1.3 kWm^{-2} above the Earth's surface level and 1000 Wm^{-2} at the surface of the Earth [4]. We can harness this solar radiation by using the solar photovoltaic (PV) system which can replace fossil fuel base generations, and it does not require refueling.

Basically, places in urban areas offered inadequate space for the installation of solar photovoltaic (PV) systems. This is due to the unavailability and high cost of suitable places. Therefore, in most of the cases, the preferred location for the installation of solar PV systems is the rooftops of buildings. Conversely, the buildings' geometrical nonuniformity makes it difficult to harness solar energy due to the shading

Table 1: Data analysis parameters [9, 12, 13].

Parameters	Values	
Bahawalpur geographical slope angle	30°	
Bahawalpur solar insolation	1981 kWh/m²/year	
Ground coverage ratio (GCR)	1.04	
Row spacing	0.1 meter	
Height	2.5 m	
Temperature model	Sandia model	
Transposition model	Perez model	
Temperature model parameters	Rack type	Carport
	a	-3.56
	b	-0.075
	Temperature delta	3°C
Weather model	TMY, 10 km grid (Meteonorm)	
Average ambient temperature	30.4°C	

Table 2: Parameters for the PV module.

Parameters	Values
Peak power watts (PMAX, Wp)	320
Maximum power voltage (VMPP, V)	37.1
Maximum power current (IMPP, A)	8.63
Open-circuit voltage (VOC, V)	45.8
Short-circuit current (ISC, A)	9.10
Module efficiency (%)	16.5

of nearby areas [5]. In urban areas, the car parking shades are vital places for the installation of solar photovoltaic (PV) systems in industrial, commercial, and educational places [6]. The United States has 11200 km^2 area for car parking spaces [3] which can be extensively used for solar energy generation.

The geographical location of Pakistan is that it has maximum duration of daylight or solar radiation that is sufficient to generate solar energy. This duration prolongs up to 8.5 hours per day with overall 2300 to 2700 hours a year. The statistics showed that this duration is almost near or equal to the maximum sunshine area in the world [7]. According to the US National Renewable Energy Laboratory, Pakistan has an average solar insolation of 5 kWh/m^2/day to 7 kWh/m^2/day [8] which is quite enough to meet the existing demand of electricity in Pakistan, yet the implementation of solar technology has suffered high capital cost.

In this research, we proposed an implementation of a solar car parking system in the Islamia University of Bahawalpur located in the Pakistan region in order to offset expensive grid electrical energy by using the solar photovoltaic (PV) system. The consistent solar insolation of Bahawalpur City has been around 1981 kWh/m^2/year, which is the 2nd highest solar insolation observed across any of the neighboring cities of the country as given in Tables 1 and 2 [9]. According to the European Photovoltaic Industry Association (EPIA), 40 GW of solar rooftop photovoltaic (PV) systems was installed globally till now, and it has been estimated to be more than 37 GW in the next five years [10]. The usage of a solar panel-based rooftop keeps increasing nowadays according to the data obtained, but still their usage for car parking shades is still uncommon. It is highly desirable to exploit the usage of PV technology to intake maximum solar energy over low cost land and site preparation. According to a survey in Pakistan, there are 17.3 million registered vehicles in Pakistan in 2015-2016 [11]. Out of the 17.3 million vehicles, 2.7 million are motor cars. There is a need for this area to be studied in the literature. It is imperative to design a model and economic analysis for solar car parking at a university level. General data used for the analysis is given in Tables 1 and 2 [9, 12, 13].

2. Overview

The 2.1 kW photovoltaic car charging station in Santa Monica, California, at a pilot scale, was considered a pioneer unit in the installation of photovoltaic (PV) systems at car parking shades to promote a solar car parking mechanism [3, 14]. It was designed for seven car parking spaces, and it had 2.1 kWp capacity. The analysis of the system simulation had been performed in "Sandia National Laboratories Albuquerque, NM" at 40° degree south due west and 22.5° tilt angle.

In Frauenfeld, a city in Switzerland, 48 car parking lots for 4240 cars were analyzed for the installation of photovoltaic (PV) systems [6]. A camera was used for taking pictures of the parking lots, and these pictures were merged into 360° panorama pictures. The number and orientation of these parking spaces were also calculated for the input in the "PV plant design software" by neglecting vertical shading elements, which can generate 5061 MWh annual energy for 15% heavier vehicles and 40% lightweight vehicles of the city.

A case study was carried out in King Abdulaziz University, KSA, that has 8% area of the campus for car parking spaces. ArcGIS, a geographical information system tool, and the TRNSYS software were used as modeling approaches for solar radiation simulation and generation of energy from the PV system. Car parking lots were comprised of already-shaded spaces and open car spaces, and both spaces had been analyzed for harvesting photovoltaic energy from the abovementioned modeling techniques which can generate 36.4 MWp maximum electric power and 66.2 GWh electrical energy [15]. An economic analysis had been done which represents a cost of US $44.5 million with the payback period of 8-16 years.

A football stadium in the University of Southern California was analyzed in 2015 for the installation of the photovoltaic (PV) system at car parking shades. After visual inspection of different car parking lots with the concern of shading effect, three parking lots had been selected. Maximum solar power utilization and economic parameters are modeled by "System Advisor Model" programed by

NREL. It had been concluded that solar energy generated from the solar car parking system can offset 31% of the total annual electricity consumption bill [16] which can reduce the generation of offset power by expensive fossil fuels. After a brief overview on solar car parking mechanisms, it has been concluded that there are some research gaps persisting in the installation of photovoltaic (PV) systems on car parking shades for maximum harnessing of solar energy, such as a need for more accurate nearby building and tree shadow analyses in site selection and integration in the national grid with grid stabilization [3, 17].

3. Methodology

In this research, a series of experiments were carried out for sizing of car parking lots, solar energy potential of a car parking lot at a proposed site, and detailed shadow analysis from nearby buildings and trees. We performed the modeling of the detailed shadow analysis, losses, and annual generation by the HelioScope software developed by Folsom Labs. The study is performed in the following cases:

Case 1. PV carport analysis without the shading effect of buildings and trees.

Case 2. PV carport analysis with the shading effect of buildings and trees.

After a detailed shadow analysis, the optimization of different car parking canopies are performed at different tilt angles for the maximum utilization of photovoltaic energy and maximum efficiency.

3.1. Carport Sizing and Structure. Normally, the size of one carport space is taken as $15\,m^2$-$18\,m^2$ [3, 15]. Here, the six-carport size is espoused for the proposed site. The double row carport is designed with a length of $19\,m^2$ and a width of $6.1\,m^2$ for three cars in one row. The total $111.5\,m^2$ space is available at the carport shade.

3.2. Case 1: PV Analysis without Shading Effect of Building and Trees. By using HelioScope by Folsom Labs, it is calculated that the total nominal 17.3 kWp solar power is available at a calculated space on a carport canopy by using 54 photovoltaic modules at a 180° azimuth angle facing south and a 30° slope angle according to geographical location at the proposed site Bahawalpur [13]. The monthly and annual solar energy generation for the Bahawalpur region is given in Table 3. The available annual solar energy yield stated in Table 3 is 28.65 MWh.

In this simulation, nearby building and tree shading effects are ignored to know the maximum nominal solar energy generation which is shown in Figure 1.

3.3. System Losses. Multiple parameters exist while converting solar radiation energy into electrical energy by using the photovoltaic (PV) system. Temperature is considered the biggest factor in the photovoltaic module working performance and the standard working module temperature is 25°C, but the proposed site exists in the hot climate zone of Pakistan and the ambient temperature module increased too much which can be calculated as follows:

$$T_m = E \cdot \left(e^{a+b\cdot \mathrm{WS}}\right) + T_a, \tag{1}$$

where T_m is the module temperature (°C), T_a is the ambient temperature (°C), E is the solar irradiance on the module (W/m^2), WS is the wind speed, a is the coefficient for the upper limit of module temperature, and b is the coefficient for which module temperature drops with wind speed.

By using equation (1) for module temperature, a 10.1% loss was countered by an increased temperature caused by the reduction in efficiency.

Reflected solar irradiance on the surface of the module is another cause of loss in the photovoltaic generation which can be calculated by the following:

$$I_{RC} = I_{GH} \cdot \alpha \left(\frac{1 - \cos\left(\sum C\right)}{2}\right), \tag{2}$$

Table 3: Monthly and annual solar generation of Case 1.

Month	Grid (kWh)
January	2152.80
February	2206.80
March	2510.70
April	2544.60
May	2501.00
June	2337.90
July	2373.40
August	2463.30
September	2599.50
October	2461.1
November	2331.70
December	2168.50
Annual	28651.30

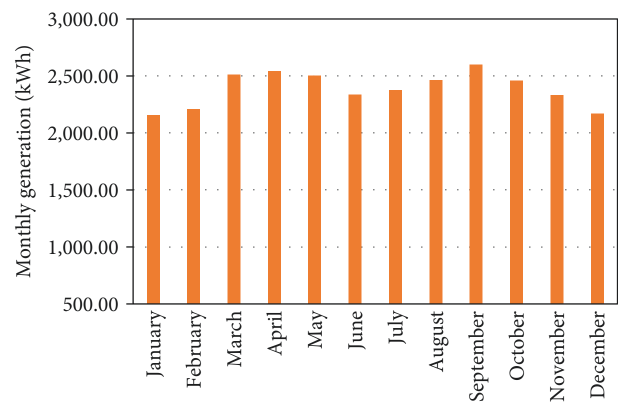


Figure 1: Monthly photovoltaic generation in Case 1.

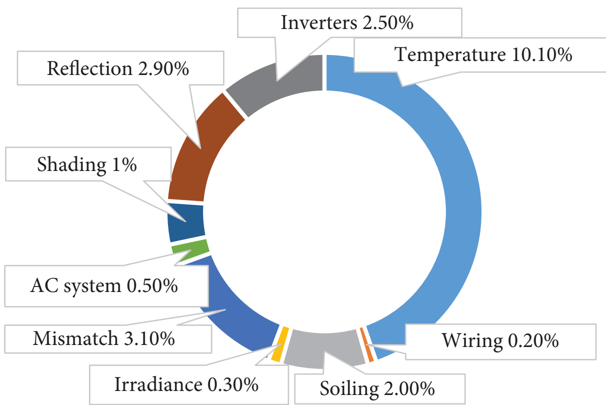


Figure 2: Overall system losses.

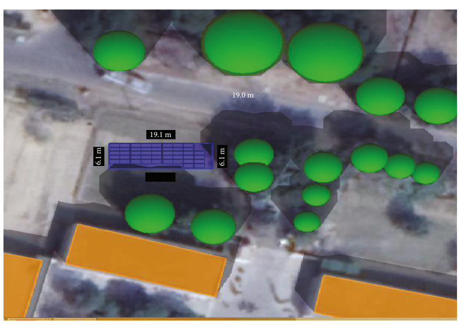


Figure 3: Shadow effect on PV modules.

where I_{RC} is the reflected irradiation on the surface of the module (W/m^2), I_{GH} is the measured global irritation (W/m^2), $\sum C$ is the collector tilt, and α is the albedo coefficient.

By using equation (2), 2.90% losses are calculated by using reflected solar irradiance on the surface of the module, reduction due to cloudy weather shading, soiling, DC to AC conversion, and other system losses which are shown in Figure 2.

Now, we will discuss Case 2.

3.4. Case 2: PV Carport Analysis with Shading Effect of Buildings and Trees. The carport site at the entrance of the department was selected which was covered by nearby tall trees and department building, so it is mandatory to perform the shadow analysis of these objects to know the diffused solar radiation on PV modules and the effect on annual solar PV generation as shown in Figure 3.

In Figure 3, the green circles are trees which have 3-5 m height. Around the blue color is the PV carport structure, and the yellow-shaded structures are department buildings with 4 m height. Here, we can clearly depict that the carport structure is suffering from the shadow of the trees, and 9 modules stopped working due to the shadow which will reduce its annual generation and performance and can damage PV modules internally.

Table 4: Monthly and annual solar generation of Case 2.

Month	Grid (kWh)
January	1740.90
February	1796.00
March	2059.70
April	2092.00
May	2041.20
June	1919.40
July	1953.10
August	2029.90
September	2134.30
October	2004.80
November	1883.80
December	1743.90
Annual	23399.00

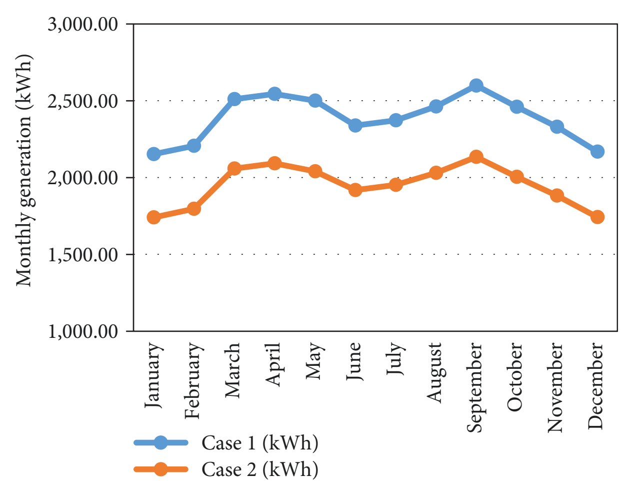


Figure 4: Comparison of Case 1 and Case 2.

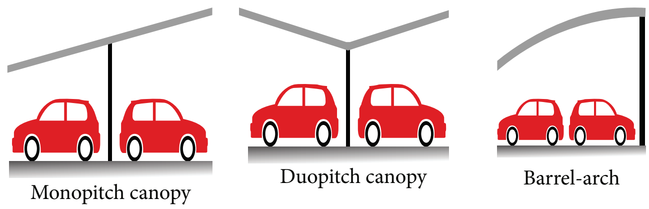
Shadow impact on photovoltaic modules can be calculated by the following equations.

$$D_{\text{iso}}^{0} = \frac{1}{2\pi}\int_{-\sum C}^{0}\int_{0}^{\pi} \sin^2(\varnothing)\cdot \sin\left(\theta+\sum C\right) d\varnothing d\theta, \tag{3}$$

$$D_{\text{iso}}^{0} = \frac{1+\cos\left(\sum C+\gamma\right)}{2}. \tag{4}$$

Equation (3) is simplified into equation (4) with shadow analysis, and it can be seen that the total annual solar energy reduced to 23.40 MWh from 28.65 MWh. More 18.3% losses were caused by the shade of trees and nearby objects. The monthly harnessing of solar energy is stated in Table 4.

The comparison of monthly PV generation for Case 1 and Case 2 is mentioned in Figure 4. It shows that there is great energy harvest difference due to the shadow of the trees and not choosing suitable places for solar carport.



(a) Monopitch canopy (b) Duopitch canopy (c) Barrel-arch canopy

Figure 5: Carport roof structures.

4. Optimization of Carport Roof Designs and Their Performance

There are two types of carport structures which are commonly used:

(i) Single row carport

(ii) Double row carport

Mostly, double row carport structure is used because it takes little space and little supporting structure is used for the parking of large number of vehicles. Based on the roof of the carport, the structures on which photovoltaic (PV) modules are installed are classified into three types:

(i) Monopitch

(ii) Duopitch

(iii) Barrel arch

It is necessary to optimize the roof designs for maximum solar photovoltaic (PV) generation. The analysis is performed for the below-mentioned carport roof designs in Figure 5 by installing 54 modules of 17.3 kWp [18].

4.1. Monopitch Canopy. A monopitch canopy has a single surface slope, which has the same slope angle at a given time. The tilt angle of the rooftop remains from 5° to 10°. Beyond this angle, it makes visual impacts and reduces shade to cars [18]. Analysis is performed at both tilt angles 5° and 10° to find the effect of the tilt angle on solar PV generation by installing modules on the monopitch roof canopy, and the azimuth angle is 180° south facing the sun and the comparison of the annual solar energy generations is shown in Figure 6.

As the tilt angle of the roof carport changes, it impacts the solar photovoltaic generation. In the monopitch canopy at tilt angle 10°, the solar PV generation is 27.18 MWh which is more than 26.43 MWh at tilt angle 5° as shown in Table 5, because, as the tilt angle changes, the irradiance level changes and the reflection of the sunrays causes a decrease in the solar photovoltaic (PV) generation.

After the given comparison, it can be concluded that the solar photovoltaic (PV) generation at a monopitch roof canopy at tilt angle 10° is maximum.

4.2. Duopitch Canopy. A duopitch canopy has two rows of roofs at the south and the north facing each other, making a valley running in both of them. Photovoltaic modules installed at the south-facing row have a 180° azimuth angle, and the angle of the north-facing modules is 360° north. Analysis is performed at both tilt angles 5° and 10° for these two roofs, and their monthly and annual generation is shown in Table 6.

At a duopitch roof canopy, solar energy at a 5° tilt angle is 25.47 MWh which is more than 25 MWh at a

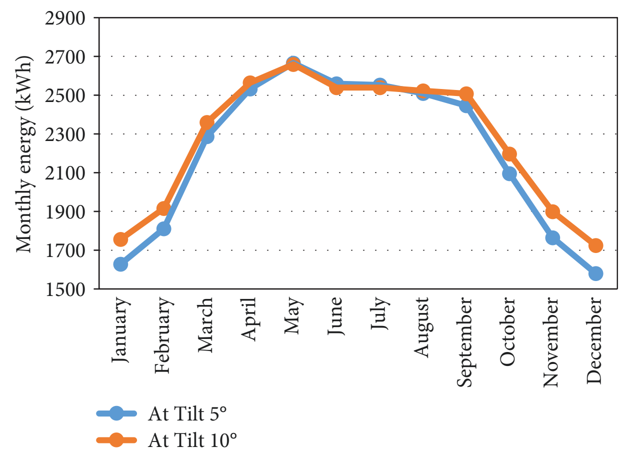


Figure 6: Comparison of monopitch PV generation at tilt angles 5° and 10°.

Table 5: Monopitch monthly generation at tilt angles 5° and 10°.

Month	Grid kWh at tilt 5°	Grid kWh at tilt 10°
January	1628.4	1755.7
February	1811.4	1915.4
March	2285.7	2359.5
April	2532.9	2563.5
May	2665.6	2659.2
June	2559.3	2538.4
July	2552.3	2539.3
August	2508.6	2522.6
September	2445.8	2507.6
October	2095.8	2196.3
November	1765.1	1899.8
December	1579.4	1723.9
Annual	26430.3	27181.2

Table 6: Duopitch monthly PV generation at tilt angles 5° and 10°.

Month	Grid kWh at tilt 5°	Grid kWh at tilt 10°
January	1483	1429.9
February	1691.6	1651.4
March	2199.1	2172.9
April	2487.9	2469.9
May	2653	2634.1
June	2559.1	2538.9
July	2545.9	2527.3
August	2479.5	2463.5
September	2372.4	2349.3
October	1980.7	1942.2
November	1607.4	1549.2
December	1411.2	1353.3
Annual	25470.8	25081.9

Table 7: Barrel-arch monthly PV generation.

Month	Grid (kWh)
January	1357.6
February	1594.1
March	2128.7
April	2446.8
May	2615.2
June	2523.2
July	2511.7
August	2446
September	2312.5
October	1885.7
November	1475.4
December	1270.4
Annual	24567.3

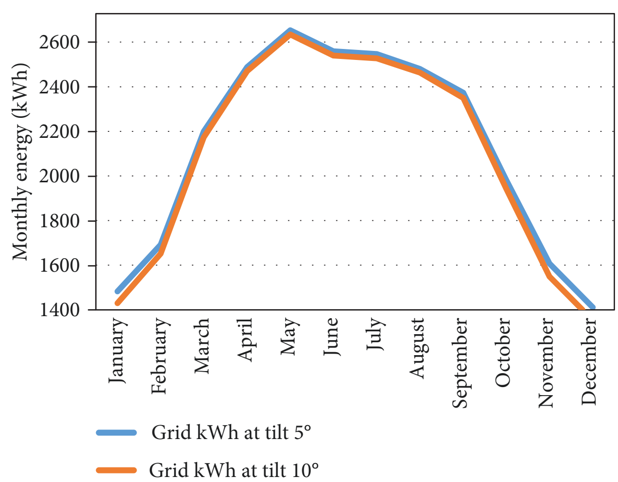


Figure 7: Comparison of duopitch monthly PV generation at tilt angles 5° and 10°.

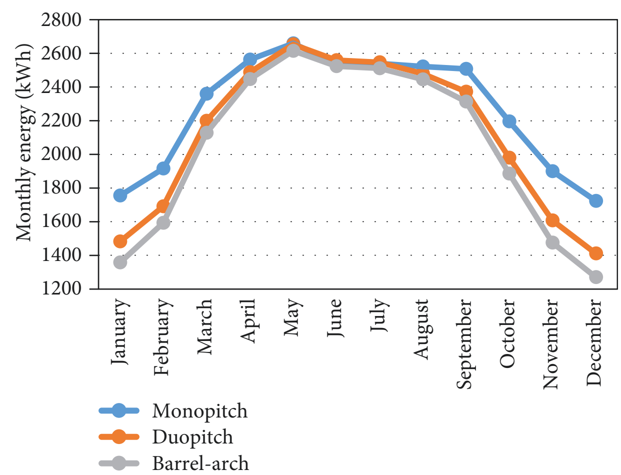


Figure 8: Comparison of PV generation of monopitch, duopitch, and barrel-arch canopies.

10° tilt angle. Because roofs of both rows at a 10° tilt angle cause the reflection of the sunrays on the surface of the north-facing row by the south-facing row, changes in the irradiance level are observed. So, energy generation at a duopitch roof canopy at a 5° tilt angle is higher as shown in Figure 7 because the reflection of the sunrays is very little between the two rows as they are not facing more towards each other.

4.3. Barrel-Arch Canopy. A barrel-arch canopy has a curved shape which has different tilt angles at each point. In this roof canopy, the first row of photovoltaic modules has an azimuth angle of 360° north at a 10° tilt angle, the middle row has a 0° tilt angle, and the last row has an azimuth angle of 180° south at a 10° tilt angle. The analysis has shown in Table 7 that the annual solar photovoltaic generation is 24.56 MWh which is lower than all the previous cases.

5. Comparison of Photovoltaic Generation on Monopitch, Duopitch, and Barrel-Arch Canopies

A detailed comparison has been done between the above-mentioned carport canopies, and the results showed that for a maximum generation of solar energy, the monopitch carport structure is the best to choose when taking the tilt angle of 10° into consideration. Duopitch yielded 93% of energy with respect to monopitch with the same installation capacity, and the barrel-arch canopy yielded 90% with respect to the monopitch canopy. Figure 8 shows that there is a great difference in energy generation in October to March because the sun in these months is more to the South Pole and the sunrays do not reach the other carports with its nominal intensity due to their physical structures which caused low yield of solar efficiency.

Table 8: Investment and payback period.

Components	Cost
Cost of PV system ($0.91/Watt)	$15727.3
Structure cost for a canopy ($4.5/sq. ft)	$5454.5
Total cost in dollars	$21181.8
Annual solar generation in $	$3212.3
Time	Year
Payback period (years)	6.6

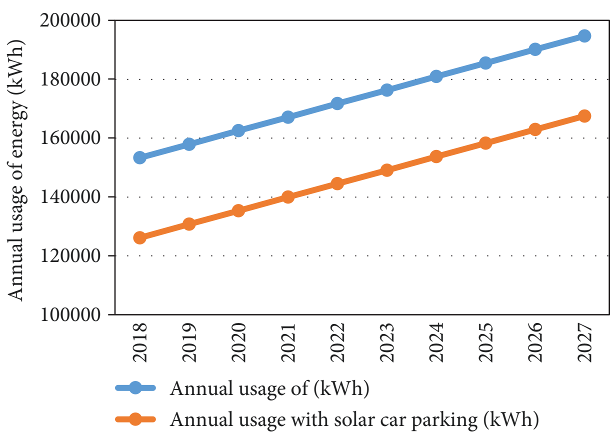


Figure 9: Comparison of annual usage of energy in the EE department by installing monopitch PV car canopies.

6. Economic Analysis

Every project depends on financial investment, its benefits, and payback period. Previous case studies and their results show that solar energy generation is possible on car parking canopies with their optimized maximum photovoltaic generation [19]. In the present case, a car parking canopy has to be built for a university department, so the structure cost is also included in the investment plan and payback period as shown in Table 8.

Cost estimation is performed with two famous vendors of photovoltaic installation by the government and the tariff structure of electricity and is taken by the regulatory body of electricity NEPRA. Based on this analysis structure of canopy and photovoltaic system, installation cost can be paid back in 6.6 years. There is 17% less annual usage of energy by the department which is shown in Figure 9 by the integration of solar energy in the system with 3% annual usage increment.

An increase in 3% usage of energy is calculated based on 5-year previous usage of the energy pattern by the EE department. While discussing the electricity bill, the payback time of investment remains the same for the first 6.6 years and after that its cost is reduced as shown in Figure 10.

For the first six years, the trend is the same because it is the payback period of investment. After which, the electricity bill is reduced by 14%. So, after a detailed economic model analysis, it is concluded that by capital investment on this PV car canopy mechanism, investment can be paid back in 6.6 years.

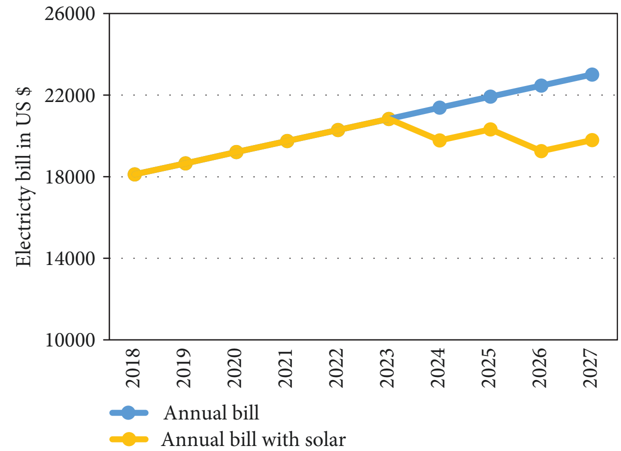


Figure 10: Comparison of reduction in annual electricity cost.

7. Benefits

Sustainable energy sources are getting used [20]. For sustainable power development, the solar car parking system is an ideal path. Social, environmental, and economical benefits are associated with it [19]. The most important benefit of solar car parking is to provide shade to cars because it reduces the internal temperature of cars in the hot sun which can cause damage to the paint works or cracks in the interior and warping [18]. Another benefit is that the cars standing in the car parking shades have a more trade value than cars standing in rain, snow, and high temperatures which devalue the paint works [21]. According to the National Electric Power Regulatory Authority (NEPRA) in 2016, Pakistan's total annual energy generation was 120621 GWh [22]. According to the abovementioned survey of vehicles, if 2.73 million car parking shades [11] are mounted with photovoltaic (PV) panels, they can generate 16.44% of the 2016 total annual generation of Pakistan. Furthermore, solar PV generation reduces the consumption of energy from the grid and reduces emission of greenhouse gases to the environment. It reduces the huge investments on fossil fuel plants in the future by the government to meet future power demands.

8. Conclusion

Solar car parking lots provide shade to cars and solar photovoltaic (PV) energy. It is beneficial for consumers as it can offset their monthly energy demand from the grid and dependency on the grid. In this research work, a detailed shadow analysis is done before the installation of solar car canopies to avoid the unwanted shadow of trees and nearby buildings and to allow the maximum utilization of solar photovoltaic energy since the shadow of trees can decrease 23.8% efficiency to the nominal rating of six car parking lots. Optimization of different car parking canopies is performed at their standard tilt angles, and it is analyzed that the monopitch canopy facing towards south at a tilt angle of 10° has the highest efficiency for the installation of new solar car parking lots.

Data Availability

The data used to support the findings of this study are included within the article. The data is cited at relevant places within the text as references.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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