GU J Sci, Part C, 11(1): 55-67 (2023)

Gazi University

Journal of Science

PART C: DESIGN AND TECHNOLOGY

http://dergipark.gov.tr/gujsc

The Parametric Design of a Photovoltaic Power System over a Parking Lot

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Article Info

Research article
Received:05/09/2022
Revision:22/11/2022
Accepted:17/12/2022

Keywords

Parametric Design
Photovoltaic
Shadow Analysis
Parking Lot Sesign
Grasshopper

Abstract

The effective planning of urban areas is important in terms of improving both the urban density and the traffic problem. Parking lots should be arranged to manage spaces and traffic at the points where the population is highly dense. On the other hand, installing rooftop solar energy plants over parking lots are highly advantageous in terms of renewable energy production. During the design process of such urban power plants, the area-energy optimization and the shading caused by surrounding buildings have direct effect on overall performance. In this study, firstly a parking lot was designed on an empty parcel within the urban area of Izmir province, with the capacity of 1.704 vehicles, 64 motorcycles and 64 electric vehicle charging stations. In addition, a solar power plant was planned over the parking lot canopies, then a power system was designed by selecting the proper photovoltaic panels and inverters. On the parametric simulation software, which was used to determine the system performance, the solar radiation and shadow simulations on the designed parking lot were run. After that, the electricity generation performances were investigated and comparisons between the parking lot parcels and the selected dates were made. In the conclusion, it was found that 7.006 photovoltaic panels placed over the canopies with an area of 24.995 m^2 are able to generate 8.084 MWh/year electricity.

1. INTRODUCTION

The demand for housing, industry, transportation, agriculture, etc. increases as a result of the high population growth rate. Concordantly, the demand for energy also increases day by day. By year 2021, the largest shares in energy production are respectively 31% petroleum, 27% coal and 24% natural gas. By the same year, the share of renewable energy sources is only 12,63% of the total. In detail, 6,83% of renewable energy sources is hydraulic energy, 2,98% is wind power and only 1,65% is solar energy. In addition, 0,47% is the share of other renewable sources (geothermal, wave energy, etc.) while the modern bio-fuels are only 0,70% [1] [2]. There are many negative effects of using fossil sources for the energy production on such a scale. First of all, the limited resources of fossil fuels are undesirable for sustainability. Moreover, the usage of these sources causes noxious gases to be released into the atmosphere and causes global warming.

The usage of the renewable energy sources as an alternative to the fossil fuels are far below the potential. This situation is more distinct for the solar energy. One of the most important parameters of the solar energy generation is the annual solar radiation values. For example, Germany has 2,75 – 3,35 kWh/m^2 annual solar radiation values and with the 58.728 MW installed solar power capacity, it generated 50.000 GWh energy in 2021 [3]. Meanwhile, Turkey has 3,13 – 5,26 kWh/m^2 annual solar radiation values but it only owns 7.813 MW installed capacity and generated 12.965 GWh energy in 2021 [4]. As seen in the given data, even though Turkey has high hours of sunshine, it does not use its potential sufficiently. In Izmir province, where this study was done, the annual solar radiation values are between 4,36 – 5,00 kWh/m^2. By year 2021, the city has installed solar power capacity of 300 MW [5]. Therefore, the solar energy plants that could be installed here can be considered more efficient compared to Turkey's average.

Solar power plants are able to be installed various places where the conditions are met. Even in urban areas, there are many ideal places for applications. Photovoltaic panels can be installed on places such as rooftops, facade elements or parking lot canopies to generate electricity. These applications add alternative function

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DOI:10.29109/gujsc.1171126

to the installed structure and prevent wasting of space [6]. Especially in large parking lots, efficient use of dead space is significant for urban development [7]. The most important problem for solar power plants in urban areas is shading. Geographical formations, trees and surrounding buildings may cast shadows on PV panels and cause efficiency losses [8]. For example, 20-30% shadow formation on a panel may result 40% loss in output power and this may also affect the PV string [9]. Therefore, solar energy investments in urban areas require decent shadow and efficiency analysis while considering all the factors affecting the site selection.

In this study, a parking lot was designed within the urban area of Izmir province and a solar power plant was planned over the parking lot canopies. After that, the efficiency of the power plant, energy generation values, shadow formation, and solar radiation values on the system were investigated with the simulations on Grasshopper, which is parametric design software. As the Grasshopper plugins, Ladybug and Honeybee were used for energy simulations and Elk was used for modeling the Geographic Information System (GIS) data [10]. This type of software analyzes many different data and variable that affects each other. Thus, they aim to find accurate results in a shorter time and shorten the decision-making process.

2. MATERIALS AND METHODS

2.1. Study Area Selection and Parking Lot Design

Within the scope of this study, a parcel was chosen as the project area in İzmir province, Karşıyaka, Mavişehir district. On this parcel, two equal parking lots with dimensions of 120 x 200 m and an area of 24.000 m^2 for each were planned. The existing path was kept and two parking lots were planned as the North and South parking lots. The reasons for choosing this district as the study field are the population and vehicle density, also the parking lot demand due to the several facilities such as shopping centers, sports halls and schools [11] (Figure 1). Moreover, it has been estimated that the study field has high solar potential due to its size and the limited number of surrounding shading factors.

Figure 1. *Satellite image of the project area and surrounding [12]*

During the design process of the parking lots, parking spaces and canopies, the latest building bylaws and Neufert building design criteria were consulted [13] [14]. Considering dimensions and constraints in the parking lot design, the greater value was chosen between both sources. As the result, the parking lot with spaces for 1704 cars (144 disabled), 64 motorcycles and 64 electric vehicle charging stations were designed. This parking lot area was divided into two parcels as North and South. The canopies are designed with a 5,6° slope to south, to get the solar radiation at a steeper angle. The PV panels aren't placed at optimum angles for the region. Instead, the maximum number of panels is aimed [15] [16]. In addition, stormwater build-up was prevented and the high-ceiled parking lots for larger vehicles such as vans, trucks, etc. were provided.

2.2. Climatic Data of the Region

The efficiency of PV panels depends on various meteorological parameters. The most important ones are temperature, wind velocity and solar radiation values [17]. Thus, the energy simulations on Grasshopper requires climatic data for calculations. The EPW (EnergyPlus Weather) files are one of the easiest methods that can be chosen for this purpose. The EPW files contain data such as temperature, humidity, solar radiation, wind velocity and direction and precipitation. These are recorded hourly in specific regions for a whole year [18]**.** The closest EPW location to the study area is Çiğli district, which is a few kilometers away. Therefore, it is chosen for the simulations (Table 1).

Table 1. *Monthly average climatic data of Çiğli/Izmir [19]*

Months	Temperature			Humidity	Wind Velocity	Solar Radiation		
	Ave.	Max.	Min.			Total	Direct	Diffuse
	(°C)			(%)	(m/s)	(W/m^2)		
1	8,14	20,40	-5,00	65,06	3,76	87,50	42,63	44,86
2	9,63	18,00	-4,00	69,84	3,51	119,22	55,76	63,46
3	13,19	25,00	0,00	61,30	3,89	169,54	88,66	80,89
4	16,06	29,00	7,00	58,75	3,54	237,28	140,45	96,83
5	21,55	34,00	7,20	57,61	3,30	257,24	142,36	114,88
6	24,77	35,00	13,00	49,17	4,13	314,57	216,74	97,83
7	27,83	37,00	17,00	50,20	3,38	323,46	242,50	80,97
8	27,84	38,00	17,60	46,97	3,81	287,89	212,46	75,43
9	22,99	34,00	13,00	60,18	3,28	223,23	150,77	72,45
10	18,30	27,20	2,00	67,36	2,33	160,83	101,68	59,15
11	13,41	24,00	2,00	72,16	2,83	106,02	59,02	47,00
12	9,89	20,00	-3,00	70,28	3,29	82,42	42,97	39,45

2.3. Photovoltaic System Selection

In order to run photovoltaic energy simulations on Grasshopper software, the number and some required data of the PV panels and inverters must be entered. However, a system design is required for the accurate data inputs. While creating a photovoltaic system, there are some limitations and criterions that must be considered. These may vary according to the specifications of the selected system components such as panels and inverters [20]. The PV systems in the study were designed considering the criterions. First of all, a 660 Wp mono-crystalline PV panel with 21% efficiency were selected to be mounted on the canopies and the same type of panel was used in all strings (Table 2).

Table 2. *Specifications of the selected PV panel* [21]

Model	**ECO-660M-66UHC** (660 W Mono-crystalline)
Dimensions (L x W x H)	2411 x 1303 x 35 mm
Max. Power	660 Wp
Open-Circuit Voltage (Voc)	46,03 V
Voltage at Max. Power (Vmpp)	38,08 V
Short-Circuit Current (Isc)	18,73 A
Current at Max. Power (Impp)	17,33 A
Max. System Voltage (V_{max})	1.500 V
Panel Efficiency (%)	%21,01

The PV systems are divided as Type-1 and Type-2 for both the North and South parking lots (Figure 2). The number and connections of the panels in these systems were decided by the calculations made according to specifications of the selected PV panel and inverter. In the Type-1 system, there are 31 panels connected in series and 5 strings connected in parallel on a canopy. This system was formed on all the 21 same sized canopies in the parking lot. Each of these strings are connected to a container type inverter with 24 DC inputs. The purpose of that is to minimize the efficiency losses caused by the parallel connection of many inverters [22] (Table 3).

The Type-2 system is placed on the long canopies in both parking lots. There are 2 systems consisting of 31 panels connected in series and 4 strings connected in parallel. This system is connected to a different inverter. The purpose of this to separate the EV charging stations in the North parking lot from the main system. Moreover, the PV system on the canopies in the South parking lot with the maximum hours of shading is also separated from the main system to prevent systemic losses and to achieve better management (Table 3).

Table 3. *Selected inverters and their specifications [21]*

Model	**SG2500HV-MV-20** *(Type-1)*	**SC60HV** *(Type-2)*
Dimensions (L x W x H)	6058 x 2438 x 2896 mm	600 x 278 x 800 mm
Max. PV Input Voltage	1.500 V	1.500 V
Max. PV Input Current	3.508 A	96,6 A
Max. AC Output Current	2886 A	79,3 A
AC Output Power	2750 kVA	66 kVA
Inverter Efficiency (%)	%98,7	%98,5

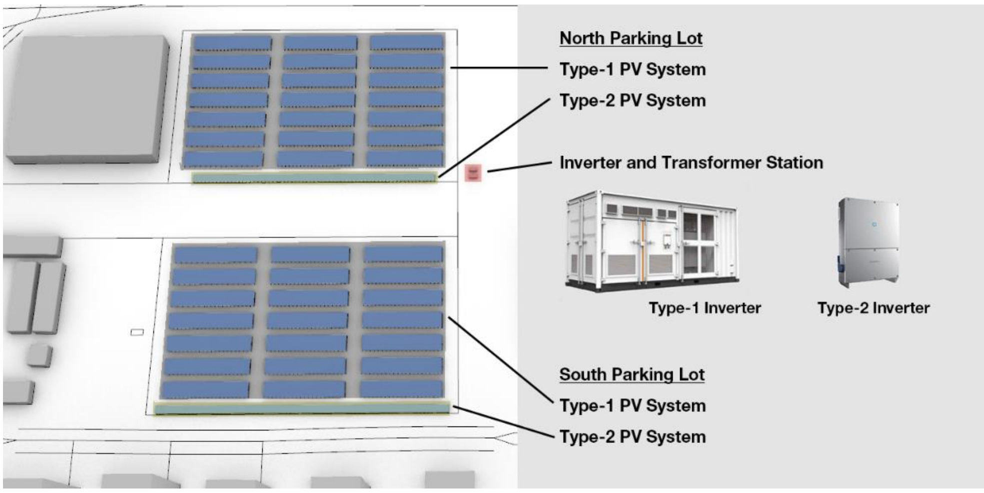

Figure 2. *The PV systems in the parking lots*

2.4. Simulations on the Parametric Design Software

The parametric design gives an opportunity to define relations between the various parameters of models and allows them to be modified interactively. When something is modified, the rest of the model reacts and updates itself according to pre-defined associative rules [23]. Some different software can be found for the parametric design. Within the scope of this study, some simulations were run on Grasshopper, which is a visual programming based parametric design software, in order to analyze different factors [24].

Basically, Grasshopper works on the "boxes and arrows" basis. On the interface of the visual programming software, boxes, objects and texts are basically considered as "input" or "restraints". These components can be connected with arrows, which are like virtual cables. Thus, the relation between these components is defined [25]. Rather than the script-based coding, this system reduces the work load and can be learned faster. One of the important points for the simulations to run properly is to define the entered data as inputs and restraints according to necessities of the setup. In addition, there are many plugins for the Grasshopper for different purposes such as modelling, architecture, energy, engineering, etc.

First step of the simulations for this study is modelling the chosen area. For this purpose, the spatial data of the parcels, buildings and roads in the district were acquired from OpenStreetMap, which is an open-source mapping platform [26] [27]. These data didn't have the height information of the buildings in the district; therefore, the height values were defined by counting the stories and entered manually to the model. Later on, the parking lot parcels and parking space markings were added. After the addition of the canopies over the parking lots, their proper positions and heights were set [28]. At this point, designing and positioning the models properly is essential to achieve the accurate results (Figure 3).

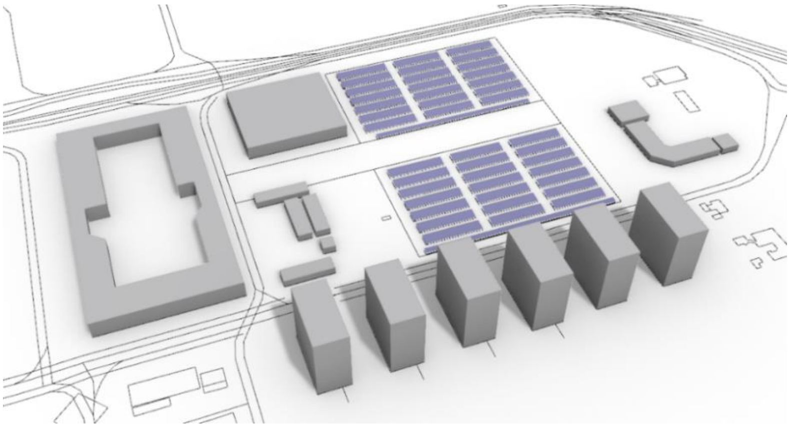

Figure 3. *The model of the parking lots, canopies and surrounding buildings, created on the Elk plug-in of Grasshopper*

Four different simulations were run on Grasshopper software with Ladybug and Honeybee plugins for the study. These are the parking lot shadow simulations, photovoltaic panel surfaces shadow simulations, solar radiation simulations and photovoltaic energy generation simulations. To get the climatic data, the EPW file for Çiğli district, which was given in Section 2.2, were used [29]. The inputs, test surfaces and time periods chosen for the simulations can be seen in Table 4.

Table 4. *Chosen inputs, test surfaces and time periods for different simulation types*

Simulation Type	**Inputs**	**Shading Elements**	**Test Surfaces**	**Simulation Dates**
Parking Lot Shadow Simulations	EPW	Canopies	Parking Lot Area	Dec. 21st, June 21st (Time: 12:00)
PV Panel Surface Shadow Simulations	EPW	Surrounding Buildings	Canopies	Dec. 21st, June 21st, March 21st, Sep. 23rd (Hourly)
Solar Radiation Simulations	EPW	Surrounding Buildings	Canopies	Dec. 21st, June 21st, March 21st, Sep. 23rd Annual (Hourly)
PV Electricity Generation Simulations	EPW, PV Specs.	Surrounding Buildings	Canopies	Dec. 21st, June 21st, March 21st, Sep. 23rd Annual (Hourly)

3. RESULTS AND DISCUSSIONS

In this section, the results of the simulations were evaluated, which was done to analyze the performance of a solar energy plant over a parking lot with Izmir province's climatic conditions. Hereinbelow the study was examined in detail as the parking lot design, shadow analysis, solar radiation analysis and power plant energy generation evaluation [30].

3.1. Parking Space Shadow Simulations

The parking space shadow simulations were done to analyze the shadows on the parking spaces casted by canopies. Thus, the functionality of the designed canopies was explored. For these simulations, December 21st 12:00 and June 21st 12:00 were selected as the day and time. Hence, the days with lowest and highest sun angle for the region were able to be analyzed. In both scenarios, it was found out that the canopies are able to cast enough shadow on the parking spaces (Figure 4).

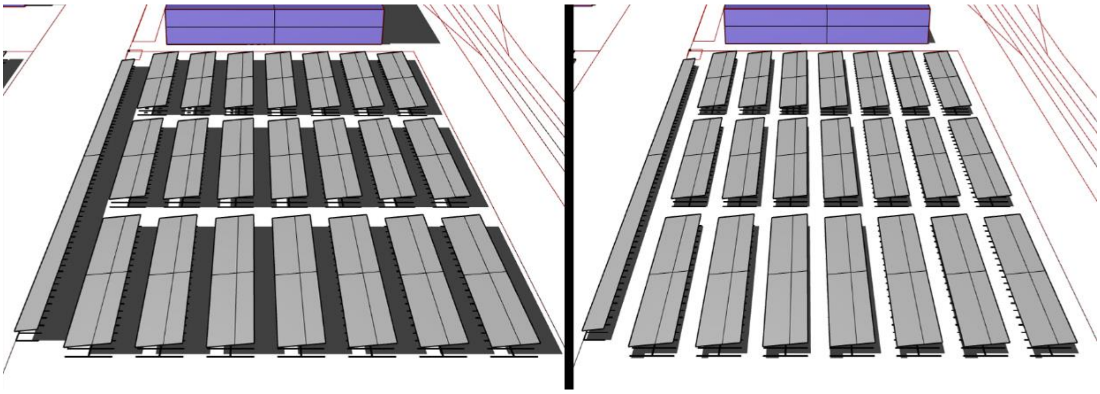

Figure 4. *Parking lot shadow simulation results (Left: Dec. 21st, 12:00; Right: June 21st, 12:00)*

3.2. Photovoltaic Panel Surfaces Shadow Simulations

In these simulations, the shadows on the parking lot canopies (hence on the PV panels) that were cast by surrounding buildings were analyzed. These shadows directly affect the overall performance of the PV panels. As the simulation dates, the 24-hour time period on December 21st and June 21st, also on March 21st and September 23rd (the equinox days) were selected. The result was given as hourly sunshine duration and shadow formation visuals (Figure 5-6-7).

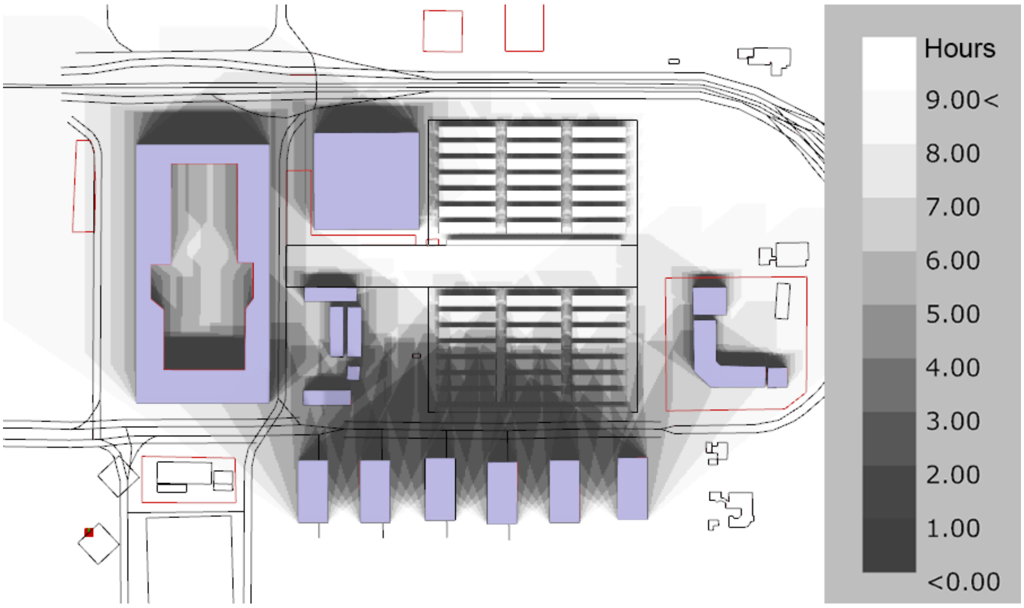

Figure 5. *Hourly sunlight duration and shadow formation on the parking lot on December 21st*

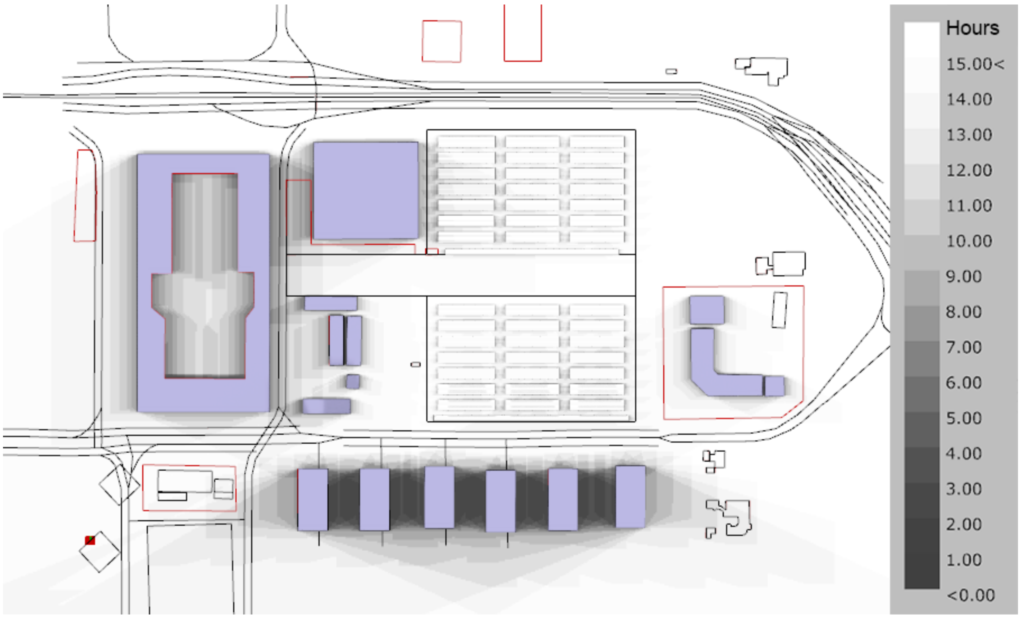

Figure 6. *Hourly sunlight duration and shadow formation on the parking lot on June 21st*

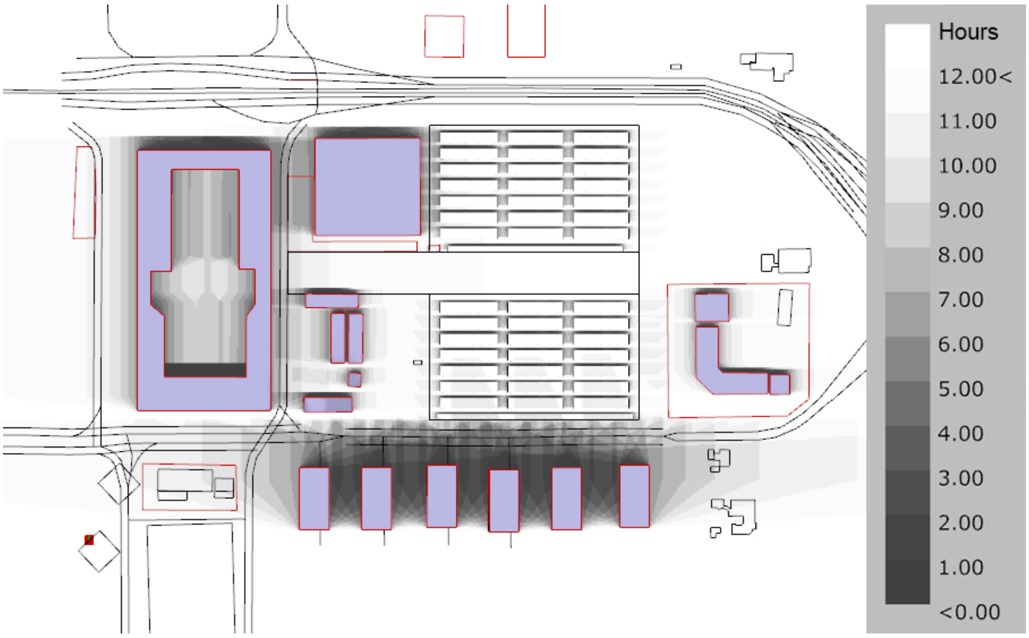

Figure 7. *Hourly sunlight duration and shadow formation on the parking lot on March 21st and September 23rd*

As seen in the simulation results, on December 21st, the shadows of the high apartment blocks located in the South of the study area are able to reach the middle rows of the South parking lot. Therefore, there is also shadow formation on the PV panels located in that part. The simulations on June 21st indicated that there are no shadows on the parking lot and PV panels cast by surrounding buildings. On the equinox days, the shadows of the apartment blocks aren't able to reach the parking lot and there is also no significant shadow cast on the PV panels. Grasshopper software processes the shadows with the same method in the following solar radiation and PV simulations.

3.3. Solar Radiation Simulations

These simulations show the solar radiation values on the selected surfaces and determined dates. The amount of solar radiation directly affects the PV panel efficiency and the energy generation amounts.

Therefore, the values on the parking lot canopies (hence on the PV panels) were taken into consideration. As the simulation dates, December 21st (Figure 8), June 21st (Figure 9), the equinox days (March 21st and September 23rd) and annual period were selected. These simulations were run on hourly periods and the results were given as 24 hours total (8760 hours total for annual simulations) (Table 5).

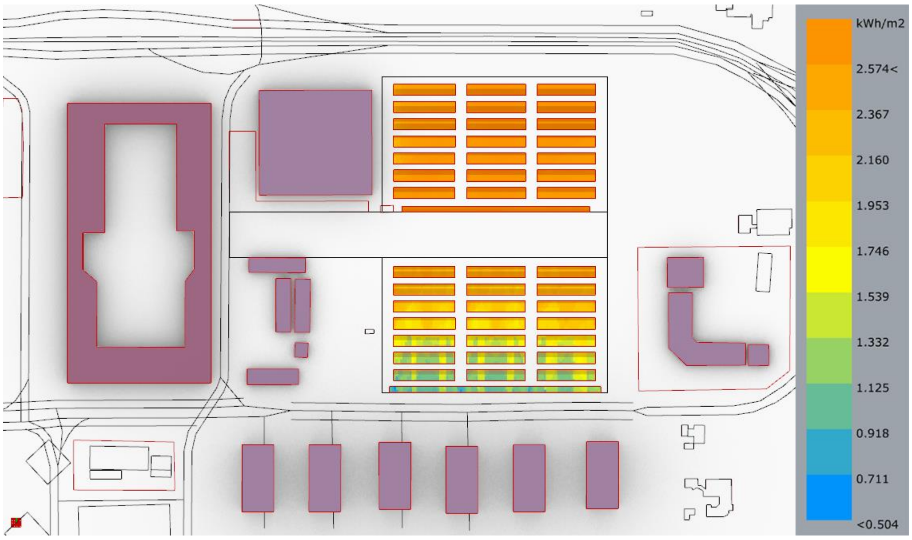

Figure 8. *Total solar radiation values on the parking lot on December 21st*

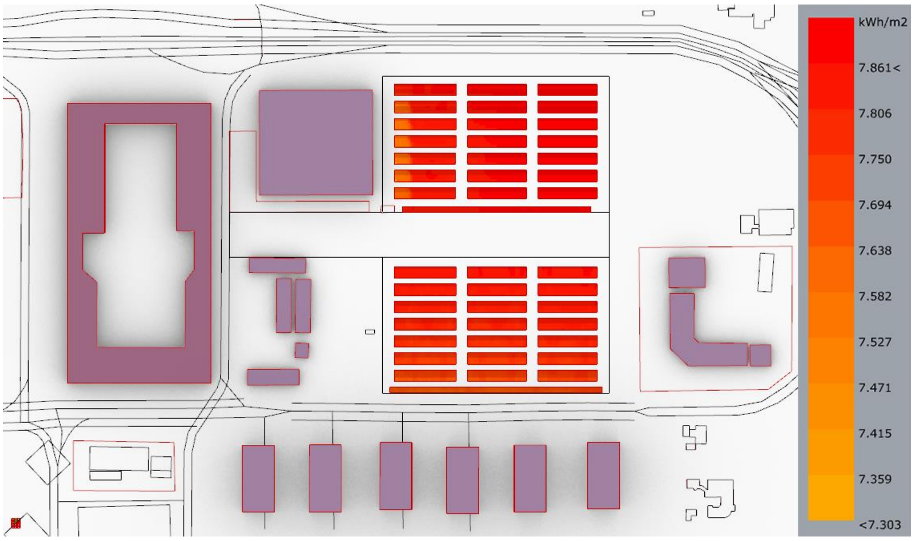

Figure 9. *Total solar radiation values on the parking lot on June 21st*

Table 5. *Solar radiation values on the parking lot canopies on selected dates*

	Dec. 21st	**March 21st**	**June 21st**	**Sep. 23rd**	**Annual**
	(kWh/m² day)				(MWh/m² year)
Parking Lots Total	2,11	5,34	7,65	3,97	1,71
North Parking Lot *(N)*	2,51	5,44	7,48	4,04	1,75
South Parking Lot *(S)*	1,71	5,23	7,83	3,91	1,66
Difference of Park. Lots (N-S)	0,80 (N)	0,21 (N)	0,35 (S)	0,13 (N)	0,09 (N)

When the values are examined, it can be seen that the North parking lot receives more radiation compared to the South parking lot on most of the days and in the annual total. Only on June 21st, the South parking lot gets higher values. The reason for that is the shadow of the sports hall, which is close to the North parking lot, forms on the panels for a short time. On December 21st, when the sun rays have the lowest angle, the difference between the two parking lots increases. The most important reason here is the shadow cast by the high apartment blocks on the South of the parking lot parcel.

3.4. Photovoltaic Energy Generation Simulations

The photovoltaic power generation simulations on Grasshopper are done as defining climatic data, shading and surrounding factors, PV system specifications, and test surfaces. Therefore, the results of these simulations are parallel to the solar radiation simulation results on the same chosen dates. The flowchart that shows the relation between the data used in the photovoltaic energy simulations can be seen in Figure 10.

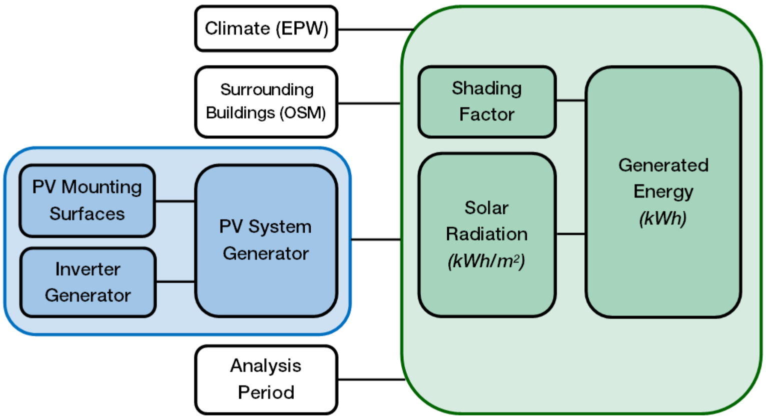

Figure 10. *Flowchart of the Grasshopper PV energy generation simulations*

Five different time periods were once again used in these simulations. These are December 21st, March 21st, June 21st, September 23rd and the annual total. In addition to solar radiation simulations, the results were evaluated separately for Type-1 and Type-2 systems in the North and South parcels. These simulation results show the total generated energy on the selected days. Same as the solar radiation simulations, they are also run at hourly intervals and the results are given as 24 hours total (8760 hours annual). The simulation results can be seen in Table 6.

Table 6. *Energy generation simulation results of the PV power systems designed on the parking lots*

	Dec. 21st	Mar. 21st	June 21st	Sep. 23rd	Annual
	(kWh/day)				(MWh/year)
North Parking Lot					
Type-1 Syst. ***(2.148,30 kWp)***	5.591,43	11.938,16	17.238,18	8.569,21	3.851
Type-2 Syst. ***(163,68 kWp)***	427,20	912,50	1.314,77	655,35	294
North Total ***(N)***	6.018,63	12.850,66	18.552,95	9.224,56	4.145
South Parking Lot					
Type-1 Syst. ***(2148,30 kWp)***	3.720,92	11.910,13	17.203,79	8.474,85	3.694
Type-2 Syst. ***(163,68 kWp)***	153,24	845,83	1.304,62	605,74	245
South Total ***(S)***	3.874,16	12.755,96	18.508,41	9.080,59	3.939
N+S Total	9.892,79	25.606,62	37.061,36	18.305,15	8.084
N-S Difference	2.144,47 (N)	94,70 (N)	44,54 (N)	143,97 (N)	206 (N)

When the results are examined, it is found that the Type-1 and Type-2 systems in the North parking lot generated more energy compared to the same systems in the South parking lot. Moreover, it can be seen that the difference between the two parking lots increased in the summer months and decreased in the winter months. The percental comparison of these simulations can be found in the next section.

3.5. Percentage Comparison of the PV Simulation Results

In this section, the results found in the previous section (Table 6) are converted to percentages to make comprehensible comparisons. Thus, the effects of the surrounding buildings and shadows on the energy generation of the PV systems, on different dates would be able to be comprehended. The percental comparison of the PV simulations can be seen in Figure 11.

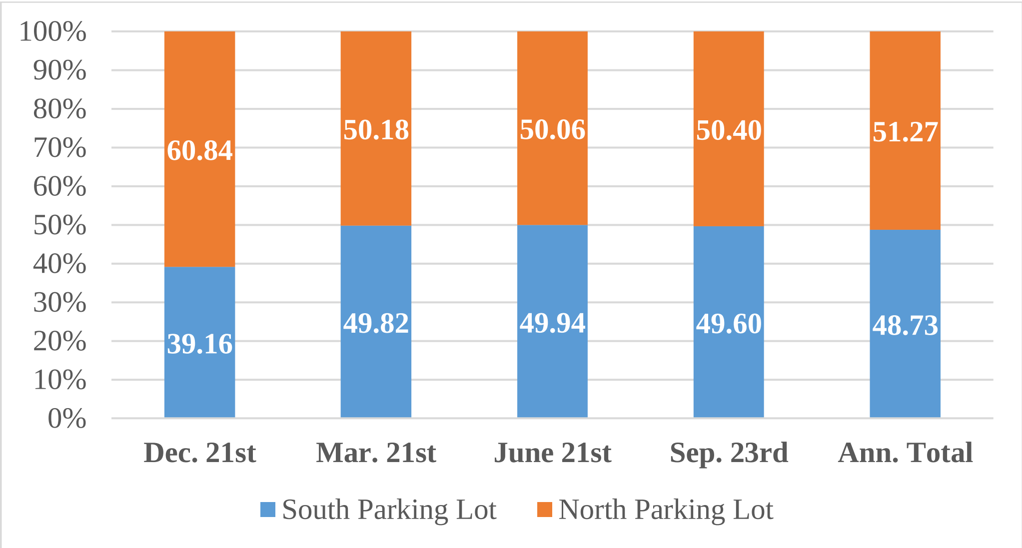

Figure 11. *Percentage distribution of the North and South PV energy generation simulations*

As seen in the results, the simulation day when the North and South parking lots generate the closest values is June 21st with a difference of 0,12% (44,56 kWh/day). On the other hand, the most different results are generated on December 21st with a difference of 21,68% (2.114,47 kWh/day). As predicted, the difference increase between percentages is caused by the shadows of the apartment blocks in the South.

In addition, there is one more point that should be considered. In the solar radiation simulations, the whole surface of canopies is chosen as the test surface. However, in the PV energy simulations, the panels are considered aligned in the center of the canopies. Since the area covered with panels are smaller than the canopy area, there are empty spaces left around the panels. On June 21st the shadow of the sports hall was cast on the canopies next to it but they are not able to reach the PV panels. Accordingly, it is possible to see a more systematic change in the PV energy simulation results compared to solar radiation simulations.

4.CONCLUSIONS

In the scope of this study, a designed parking lot and integrated solar energy plant have been investigated in terms of vehicle capacity and electricity generation performance. The project was considered a noticeable facility in order to solve the parking problem in the district with its spaces for 1704 vehicles, 64 motorcycles and 64 electric vehicle charging stations. Besides, it offers renewable solutions for future necessities with the expandable capacity of the charging stations.

Considering the results of the simulations, there is no significant shadow formation cast by surrounding buildings found in the summer months, according to shadow simulations. In the winter months, when sun rays have a lower angle, the shadows of the buildings are only formed on one parking lot parcel. However, the solar energy plants in the two parking lots were planned separately and the facility in the other parcel is able to keep functioning.

Since Izmir province is located in a region with a high number of sunshine hours, high solar radiation values are measured. As a result of simulations, the solar radiation values up to 1.774 kWh/m^2 in annual total were calculated on the canopies with 24.995 m^2 area. When considering the importance of solar radiation in the electric generation of PV panels, a facility installed in such a large area would be defined as a significant renewable energy source. With the energy generation simulations, it was determined that 8.084 MWh/year of electricity is able to be generated by the 7.006 units of 660 Wp PV panels installed on the canopies. In the district where the solar power plant is designed (Mavişehir), the population is 14.129 and there are 11.626 lots with an electricity subscription by the year 2021. The electricity consumption of the neighborhood is approximately 41.853 MWh/year [31]. As the proposed plant is able to generate 8.084 MWh/year, it can cover around 19,32% of the total demand. Therefore, it can be stated that, this power plant is able to be a significant facility for the electricity demand of the region. Since this facility uses a renewable energy source instead of fossil fuels, it will contribute to preventing environmental pollution and carbon emissions.

This study also aims to demonstrate the importance of simulation software at the design stage of renewable energy applications. The usage of this kind of software helps save time and money as they shorten the decision-making process. Moreover, they help to define possible problems and provide better system optimization. Especially, on parametric design software like Grasshopper, many different data and factors can be combined to run simultaneously for more complex analysis. Thus, the results of simulations are more accurate and closer to actual scenarios compared to standard simulation methods.

ACKNOWLEDGEMENTS

This article was written based on the thesis study named "Parametric Design of Photovoltaic Power System over Parking Lot" which was conducted at Ege University Graduate School of Natural and Applied Sciences, Department of Solar Energy as the MSc. thesis in 2022.

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