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Research Article

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Rooftop solar PV system planning with 3D visualization using PVSOL (Case study in Syria)

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Abstract In this work, modeling and simulation with a three-dimensional visualization of a photovoltaic solar energy system installed on the building's roof of one of the government scientific institutions in Syria was carried out using the PVSOL software. Four possible configurations for placing the solar panels on the building's roof with a three-dimensional view were studied. In two configurations the panels were oriented to the direct South. In the other two configurations the panels were oriented parallel to the edge of the building (azimuth -13°). The optimal tilt angle of the panels and the appropriate spacing between the panel rows (in the case of horizontal or vertical placement of the panels) were determined. The modeling results showed that the first configuration (the panels were oriented to the direct South and placed horizontally) achieved the highest value of the performance ratio and the lowest value of shading losses with a net power generated annually of 98225 kWh and a total capacity of 51.23 kW. The calculated economic indicators showed that the proposed PV system with the selected configuration is profitable and economically feasible.

Keywords Syria, 3D visualization, PVSOL, PV panels, solar.

1. Introduction

The growing shortage of fossil fuels, global warming problems and environmental degradation have led to increased interest in renewable energy sources, as a new report released by the International Renewable Energy Agency (IRENA) revealed that the total capacity of renewable energy plants reached to 3372 GW by the end of 2022 (about 900 GW of wind energy and 1053 GW of solar energy), increasing the renewable energy stock by a record rate of 295 GW or by 9.6 % (about half of this capacity was added in Asia and China was the largest contributor). This new capacity added from renewable energy sources accounted for 83% of the total new installed capacity last year [1]. Thus, this growth at record levels despite the uncertainty surrounding the world confirms the decline in the trend towards generating energy from fossil fuels. Although hydropower accounts for the largest share of the total global installed capacity of renewable energy at 1250 GW, solar and wind energy continue to dominate the new installed capacity, together contributing to 90 % of the total capacity in 2022. The installed capacity of solar energy ranked first with an increase of 22%, followed by wind energy, whose installed capacity increased by 9 % [1]. Solar PV accounted for most of the increase in renewable energy in 2022, with an increase of 191 GW to a total of 1047 GW [1]. Solar electricity generation via solar photovoltaic panels has the advantages of being fuel-free, environmentally friendly, inexhaustible, scalable and easy to maintain in addition to reliable operation. However, solar photovoltaic panels have some disadvantages, such as low yield, high investment cost and sensitivity to climate changes [2]. In the Fifties of the last century photovoltaic solar panels were used only in space and satellite applications, but in the seventies they also began to be used in terrestrial applications. Today photovoltaic solar cells or panels are used to provide energy for many applications that are connected to or isolated from the public electrical grid. The total installed cost of solar photovoltaic projects has decreased from 4808 $/kW in 2010 to 857 $/kW in 2021, i.e. by 82 %, in addition to the decrease in the cost of electricity production (LCOE) from 0.417 $/kWh in 2010 to 0.048 $/kWh in 2021, i.e. by 88% due to the decrease in the prices of solar photovoltaic panels and the increase in its efficiency [3]. The capacity Factor of solar photovoltaic projects increased from 13.8 % in 2010 to about 17.2 % in 2021 [3]. Crystalline silicon solar panels are also considered the most widely used in the local and global market due to their low price, occupying around 90 % of the production market.

Syria possesses significant renewable energy sources due to its geographical and climatic nature. In 2010 hydroelectric power occupied an important place in the production of electrical energy in Syria, where hydroelectric power plants had a capacity of about 1500 MW (15% of the total capacity) and were producing about 2604 GWh of electricity (6% of the total production) [4], currently, due to the war, there is no possibility to benefit from these plants. Thus, gas, steam and combined-cycle power plants are the only ones that provide electricity to the country with an available installed capacity of about 4400 MW, depending on the technical situation and available gas quantities [5]. As for the electricity production, it has decreased from 47000 GWh in 2010 to about 25000 GWh in 2020 as a result of the unjust economic blockade and the war that the country has experienced over the past decade [5]. Wind and solar energy resources have not yet been significantly invested, so conducting computer and field studies on the optimal implementation of projects utilizing these resources is a priority for achieving economic development and covering the electricity production deficit. As part of the government's support for renewable energy projects and its strategy to encourage investment in these projects to serve all sectors, several laws and regulations have been issued to serve this purpose. Additionally, several photovoltaic solar energy projects, which connected to or isolated from the grid, with different capacities have been implemented in open lands and on the surfaces of some hospitals, government buildings and industrial facilities.

Modeling and simulation using advanced engineering software is considered the first and fundamental step before implementing any photovoltaic solar energy project in reality. These programs provide the ability to conduct detailed technical and economic analysis of the system by studying its performance and all its parameters. The PVSOL software is one of the most important leading programs used by planners and engineers worldwide for the planning and design of efficient photovoltaic solar energy systems, due to the following advantages [6]: 1) a very modern database that includes a list of the latest types of photovoltaic panels, inverters, and batteries produced by manufacturers, 2) the possibility of a three-dimensional drawing using google maps and conducting a high-resolution 3D shading analysis throughout the year, 3) calculating the optimal positioning of the panels within the available space, 4) the ability to choose the type of system used, whether it is grid-connected without batteries, grid-connected with batteries, or off-grid with batteries and generators, 5) conducting an economic analysis of the system, taking into account the feed-in tariff for each country, 6) a huge and updated weather database, 7) presenting a technical and financial report for the system.

There are a number of studies and scientific researches in which this program or other similar programs have been used for the purpose of planning and designing photovoltaic solar energy systems located on building surfaces or in open areas. In [7] an assessment and calculation of the technical and economic parameters of a grid-connected solar photovoltaic plant with a capacity of 300 kW was made in Umm Al-Zaytun village in As-Suwayda province using the PVsyst program. The results showed that the plant, consisting of 720 solar panels, provides energy of 493 MWh per year with a capacity factor of 18.7%, taking into account all losses estimated at 22 %. The economic analysis also showed that the powerplant provides electricity to approximately 220 people, reduces carbon dioxide emissions by approximately 321 tons per year, and saves around 43 tons of oil equivalent. The net income from the project was about 190000 $, with a payback period estimated at 11 years and a cost of 0.094 $/kWh of generated energy. In [8] a simulation was conducted for the design of a grid-connected photovoltaic solar energy system on the faculty building at Marmara University in Istanbul using the PVSOL software. The study indicated that the project, with a capacity of 84.75 kW, is capable of supplying 13.2 % of the annual electricity consumption of the university building, resulting in an annual electricity savings of approximately 90298 kWh, which costs around 7296 $. In [9] a hybrid photovoltaic-diesel system was studied in a remote area of the Amazon region in Brazil using the HOMER software as a tool to simulate the system comprising of photovoltaic solar panels, lead-acid battery bank, diesel generator, and electrical load. The results showed that the optimal strategy is to supply 85.6 % of the load using solar power and only 14.4 % through diesel generators. In [10] the possibility of using photovoltaic solar energy systems on rooftops in the residential sector in the Kingdom of Saudi Arabia was verified, taking into account the two main types of buildings (apartments and villas), as well as considering different structural, service, and cultural standards. The study used remote sensing techniques and geographic information systems to collect building surface data for a specific area in Al Khobar city, covering 33000 housing units. The PVSOL software was used to model the photovoltaic panels on building surfaces and determine the shading effect. The results showed that 21 % and 28 % of the surfaces of villas and apartments, respectively, can effectively be used for photovoltaic applications. The total surface area of residential buildings in the study area, which is 14.21 square kilometers, can produce 796 GWh of electricity annually using photovoltaic panels.

Previous studies and researches show the importance of using simulation programs to study the systems and applications of solar PV panels, so in this paper the PVSOL program will be used to conduct a simulation with a three-dimensional visualization of a solar PV system installed on the roof of a building of one of the government scientific institutions in city of Damascus in Syria. This work will contribute to raising awareness about the importance of implementing photovoltaic solar energy projects on government buildings' rooftops in Syria, and the need to utilize the available space on these surfaces and the high solar radiation they receive to generate electricity through photovoltaic solar panels. Consequently, it will help in partially covering the existing electricity shortage and improving the electricity situation in the country.

2. Methodology and calculations on the PVSOL program

2.1. Enter the coordinates of the site, determine climatic data and the type of proposed system

The selected building coordinates (latitude & longitude) of the chosen government scientific institution are entered into the PVSOL program, and based on them, the climatic data for the selected location is determined, which is data for a period of twenty years. It is evident from the climatic data for the location that the global annual solar radiation incident on a horizontal surface is equal to 2063 kWh/m2/year, and the average annual temperature is 16.7°C. Also, in the first window of the program, the type of proposed system is determined, which is a grid-connected PV system. This system was chosen because the government electricity supply is uninterrupted to the building (exempt from power rationing), and it helps to save costs for the project since there is no need to use batteries.

2.2. Determine the optimal tilt angle of the panels and choose the type of PV panel

Based on the site coordinates, the program determines the optimal tilt angle of the panels that achieves the maximum annual global solar radiation incident on the inclined surface (panels). Table 1 shows the annual global solar radiation incident on the panels, which the program calculates when using different tilt angles.

Table 1: Selecting the optimal tilt angle of the panels

Tilt angle, °	25	26	27	28	**29**	30	31	32	33	34	35
Annual global solar radiation, kWh/m^2/y	2257.5	2259.2	2260.4	2261	**2261.1**	2260.6	2259.6	2258	2255.9	2253.2	2249.9

The table 1 shows that the optimal tilt angle, which achieves the highest annual global solar radiation incident on the inclined surface (panels), is the angle of 29°, which corresponds to the calculated angle according to the following equation [11]:

Optimal tilt angle (northern hemisphere) = 1.3793 + Φ(1.2011 + Φ(-0.014404 + Φ0.000080509)) = 1.3793 + 33.49*(1.2011 + 33.49*(-0.014404 + 33.49*0.000080509)) = 28.5 ≈ 29°

Where: (Φ = latitude=33.49°).

Therefore, this tilt angle was chosen for the proposed project.

After studying the local market and the available high-quality types of panels, a half-cut cell technology panel with a capacity of 545 W from the international company Longi was chosen for the proposed project, and it has the characteristics shown in Table 2.

Table 2: Longi PV panel specifications

Nominal power at STC	545 W	**Number of cells**	144 (6*24)
Technology	Monocrystalline/ half-cell/ 9 bus bar	**Module efficiency**	21.3 %
Reference conditions	1000 W/m^2, 25°C	**Open circuit voltage temperature coefficient**	-0.270 % / °C
Short-circuit current	13.92 A	**Short circuit current temperature coefficient**	0.048 % / °C
Open circuit voltage	49.65 V	**Max power temperature coefficient**	-0.350 % / °C
Power tolerance	0 ~ +5 W	**Dimension**	2256*1133*35 mm
Voltage at max power, Vmp	41.8 V	**Weight**	27.2 kg
Current at max power, Imp	13.04 A	**Power degradation**	0.55 %/year

2.3. Choose the optimal positioning of PV panels with 3D visualization and conduct shading analysis

In this step, an image of the building is inserted in PVSOL from Google Maps, and a three-dimensional model is created that simulates the building (subject of the study), taking into consideration the height of the stair house and the objects on the surface of the building (cooling and air conditioning equipment). Four possible configurations for placing the panels on the building's roof were studied. Two of these configurations had the panels facing south and positioned either vertically or horizontally, while considering the appropriate spacing between the panel rows. The other two configurations had the panels oriented parallel to the building edge (azimuth -13°) and positioned vertically or horizontally with the correct distance between rows. Shading analysis, caused by neighboring panels and objects, was performed in each configuration. The program shows on each panel a percentage value, representing the annual direct solar radiation reduction due to seasonal shade frequency on the panels. The optimal distance between rows was determined in the case of horizontal or vertical installation of panels based on the panel dimensions, the sun's elevation angle, and the panel's tilt angle, as shown in figure 1. It is clear from the figure 1 that the optimal distance between the rows of panels (mounting support clearance, d1) is 0.844 m when the panel is horizontally positioned, and 1.68 m when the panel is vertically positioned. Based on the calculated distance between the rows, the type of used panel, and the available area of building's roof, the mentioned four configurations were implemented one by one with shading loss calculation throughout the year as shown in figures (2 to 5). It is observed from the third and fourth configurations that when the panels are oriented parallel to the edge of the building, a larger number of panels can be placed within the available space (an increase of 10 panels compared to the first and second configurations) to achieve a total capacity of 56.68 kWp with 104 panels. Whereas, in the case of panels oriented to the direct south (first and second configurations), the number of panels was 94 with a total capacity of 51.23 kWp.

The case of vertical installation of PV panels

Input

Reference	Value	Unit
Module Mount Width b	2.256	m
Mount Height h	1.095	m
Resulting Module Inclination β	29.0	°
Resulting Module Orientation	180.0	°
Inclination of Mounting Surface β_1	0.0	°
Orientation of Mounting Surface	77.1	°
Solar Elevation Angle γ	33.07	°
Solar elevation angle applies to new	21/12/ 12:00	-

Results

Reference	Value	Unit
Depth of Row $d - d_1$	1.973	m
Mounting Support Clearance d_1	1.680	m
Row Spacing d	3.653	m

The case of horizontal installation of PV panels

Input

Reference	Value	Unit
Module Mount Width b	1.133	m
Mount Height h	0.550	m
Resulting Module Inclination β	29.0	°
Resulting Module Orientation	180.0	°
Inclination of Mounting Surface β_1	0.0	°
Orientation of Mounting Surface	77.1	°
Solar Elevation Angle γ	33.07	°
Solar elevation angle applies to new	21/12/ 12:00	-

Results

Reference	Value	Unit
Depth of Row $d - d_1$	0.991	m
Mounting Support Clearance d_1	0.844	m
Row Spacing d	1.835	m

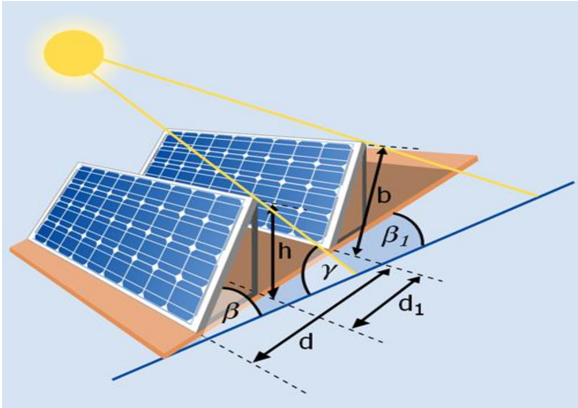
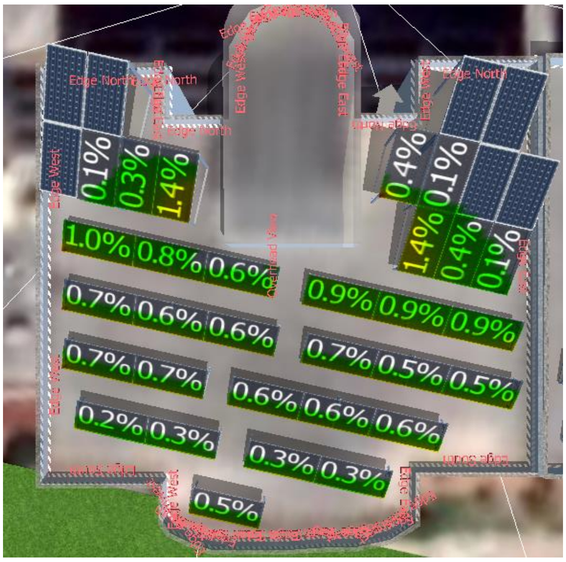
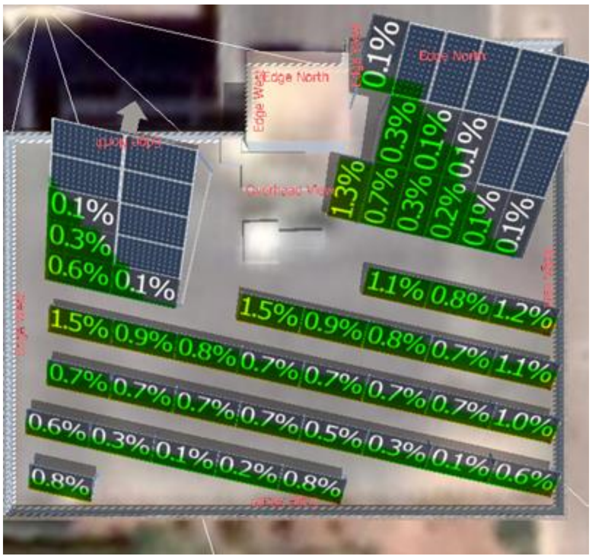


Figure 1: Calculating the optimal distance between the rows of PV panels in the case of horizontal or vertical panel placement.

First configuration: Panels are directed towards the south and positioned horizontally

Percentage value of annual direct solar radiation reduction due to shading





Number of PV Modules	94	Power 51.23 kWp
Orientation	180°	Azimuth 0 °
Inclination	29°	
Installation Type	Mounted - Roof	

Total capacity obtained from this configuration: 51.23 kW_p

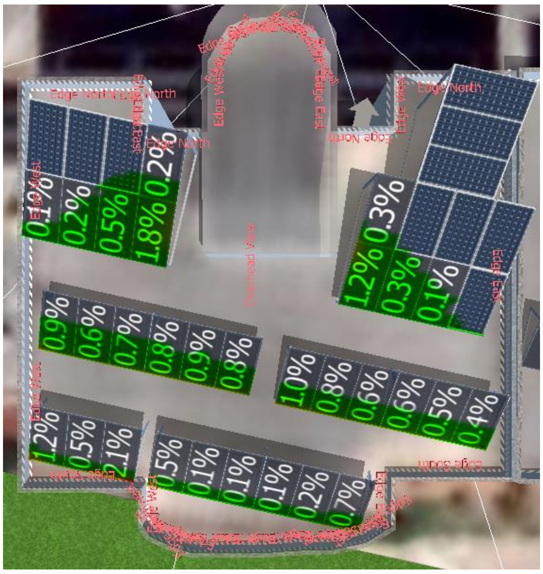
Total number of PV panels: 94 panels

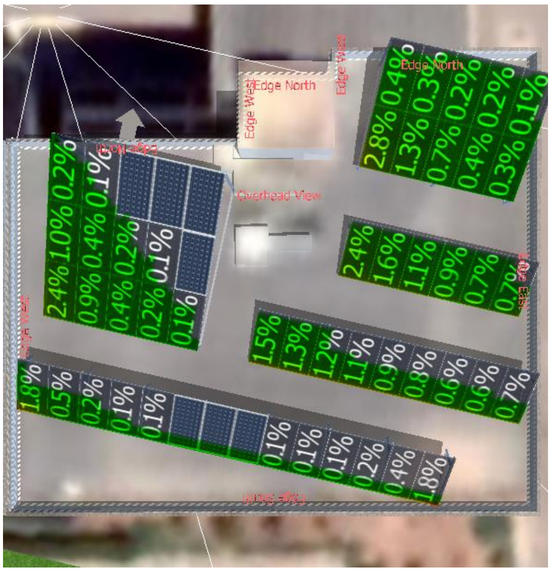
Total surface area of PV panels: 240.3 m^2

Figure 2: First configuration: PV Panels are oriented to the south and placed horizontally

Second configuration: Panels are oriented towards the south and placed vertically

Percentage value of annual direct solar radiation reduction due to shading





Number of PV Modules	94	Power 51.23 kWp
Orientation	180°	Azimuth 0 °
Inclination	29°	
Installation Type	Mounted - Roof	

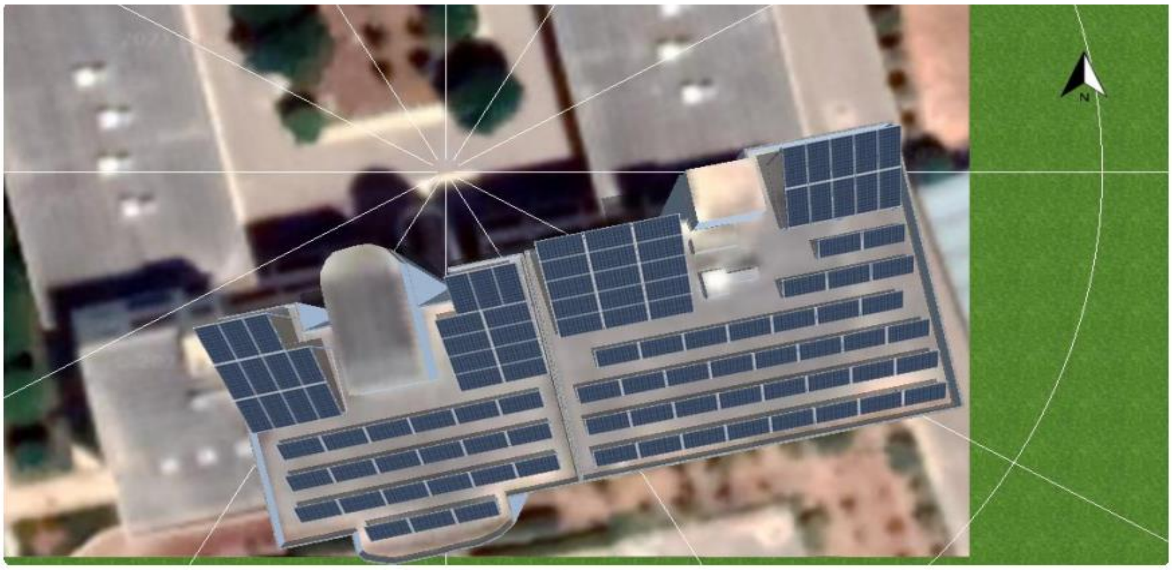
Total capacity obtained from this configuration: 51.23 kW_p

Total number of PV panels: 94 panels

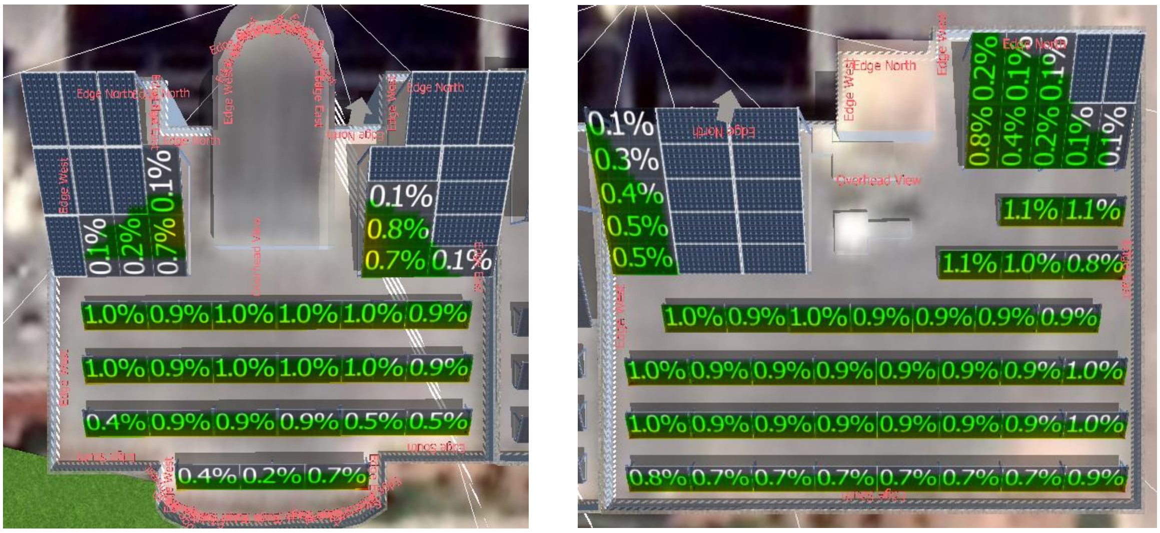
Total surface area of PV panels: 240.3 m^2

Figure 3: Second configuration: PV Panels are oriented to the south and placed vertically

Third configuration: Panels are oriented parallel to the building edge (azimuth -13°) and positioned horizontally



Percentage value of annual direct solar radiation reduction due to shading



Number of PV Modules	104	Power 56.68 kWp
Orientation	167°	Azimuth -13 °
Inclination	29°	
Installation Type	Mounted - Roof	

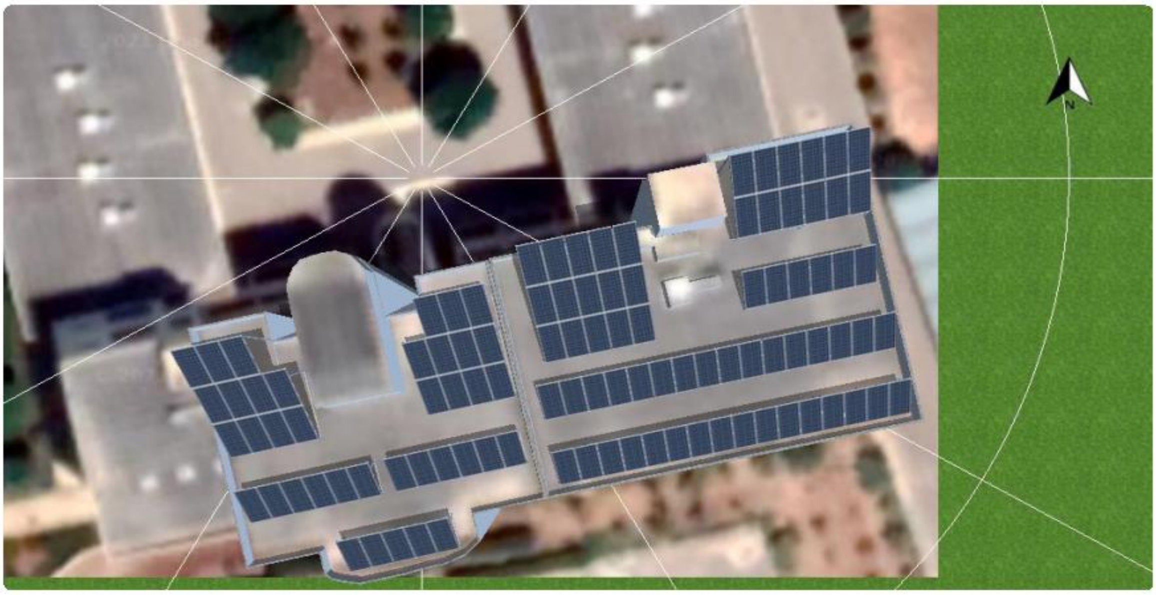
Total capacity obtained from this configuration: 56.68 kW_p

Total number of PV panels: 104 panels

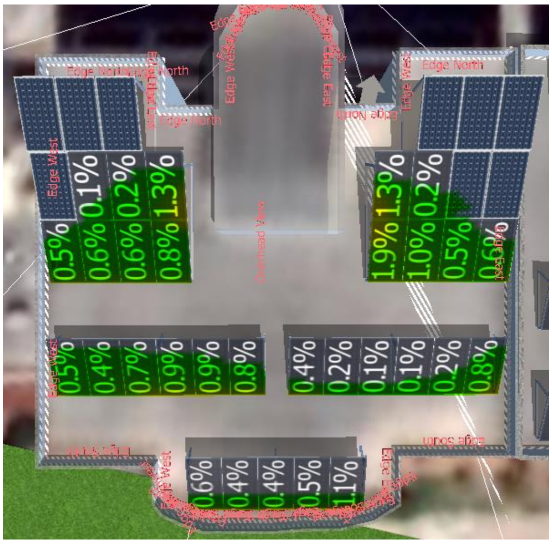
Total surface area of PV panels: 265.8 m^2

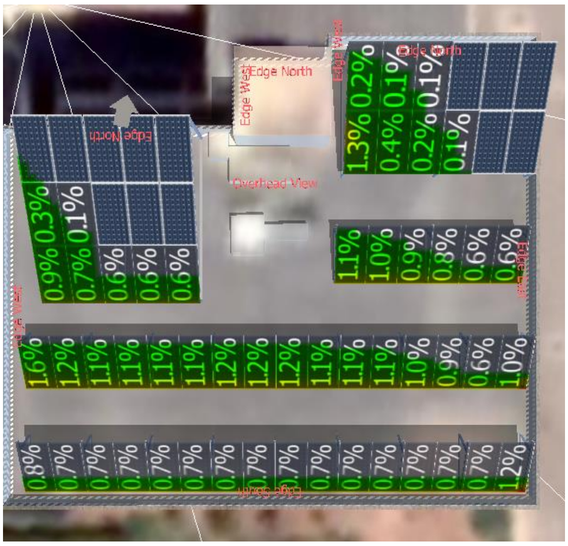
Figure 4: Third configuration: Panels are oriented parallel to the building edge (azimuth -13°) and positioned horizontally

Fourth configuration: Panels are oriented parallel to the building edge (azimuth -13°) and placed vertically



Percentage value of annual direct solar radiation reduction due to shading





Number of PV Modules	104	Power 56.68 kWp
Orientation	167°	Azimuth -13 °
Inclination	29°	
Installation Type	Mounted - Roof	

Total capacity obtained from this configuration: 56.68 kW_p

Total number of PV panels: 104 panels

Total surface area of PV panels: 265.8 m^2

Figure 5: Fourth configuration: Panels are oriented parallel to the building edge (azimuth -13°) and placed vertically

2.4. Determine the appropriate inverter for the system and cable cross-sections

After studying the inverters available in the local market and according to what is available in the program database, and since the total capacity of any of the previous four configurations is about 50 kW, the on-grid inverter was selected from SOFAR solar company with a capacity of 50 kW. Table 3 shows the characteristics of this inverter.

Table 3: SOFAR 50000TL Specifications

Input (DC)	
Recommended max. PV input power (Wp)	66500
Max. DC power for single MPPT (W)	22000/16000/16000
Number of MPP trackers	3
Max. input voltage (V)	1000
Rated input voltage (V)	600
MPPT operating voltage range (V)	250 V - 960 V
Max. input MPPT current (A)	40A/30A/30A
Number of DC inputs	4/3/3
Output (AC)	
Rated power (W)	50000
Max. AC power (VA)	50000
Rated grid voltage	3/N/PE, 220/380Vac, 230/400Vac
Rated frequency	50/60 Hz
European weighted efficiency	98.3 %

After selecting the type of inverter, the number of PV strings and the number of panels in each string for each of the previous four configurations were determined in accordance with the chosen inverter and the following design criteria:

- The total current of the panels should not exceed the maximum input current of the inverter.
- The ratio of the photovoltaic panels' capacity to the inverter capacity (Sizing Factor) should not be less than 100%.
- The maximum power Point (MPP) voltage for each PV string must fall within the voltage range of MPP Tracker of the inverter.
- The open circuit voltage of each PV string should not exceed the maximum input voltage of the inverter. The maximum value of the open circuit voltage is calculated at a temperature of -10 degrees Celsius.

Table 4 shows how the PV panels are connected together into strings and connected with the MPP tracker entrances of the inverter so as to achieve the previous design standards for each of the four configurations.

Table 4: Strings and panels number for each configuration and sizing factor

	Sizing Factor	Strings and panels number for each MPP tracker of inverter
First configuration	102.5 %	MPP 1: 2 × 15 MPP 2: 2 × 16 MPP 3: 2 × 16
Second configuration	102.5 %	MPP 1: 2 × 15 MPP 2: 2 × 16 MPP 3: 2 × 16
Third configuration	113.4 %	MPP 1: 2 × 17 MPP 2: 2 × 17 MPP 3: 2 × 18
Fourth configuration	113.4 %	MPP 1: 2 × 17 MPP 2: 2 × 17 MPP 3: 2 × 18

Based on the study of the proposed building, it was estimated that each of the previous four configurations needs about 240 m of copper string cables and about 25 m of three-phase copper alternating current cables. Based on these lengths the appropriate cables cross-sections and the resulting losses were calculated. DC cables cross-section for each string was 4 mm2, AC cable cross-section was 16 mm2 and the losses resulting from all cables were 609.3 W. for illustration, figure 6 shows the circuit diagram of one of the four implemented configurations, which is the first configuration.

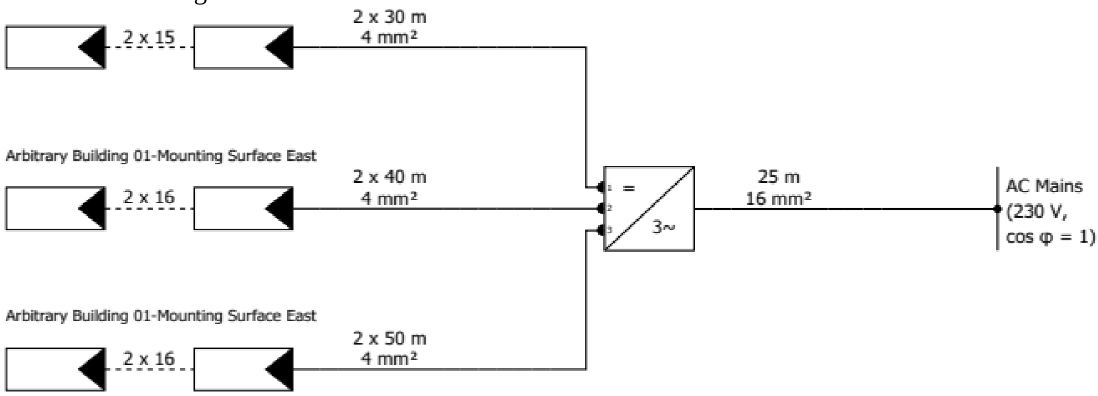


Figure 6: Circuit diagram for the first configuration

3. Results of simulation in PVSOL

The energy flow within the system for the previous four configurations and the all losses to finally get the net generated electrical energy were obtained by simulation in PVSOL. The most important technical results can be summarized in Table 5 for discussion and analysis. Table 5 shows that the third and fourth configurations have an annual generated energy injected to grid greater than the first and second configurations, and this is normal because they have a larger number of panels and a larger total capacity, but the negative effect of the displacement of the panels from the South is clearly shown in reduction of solar radiation incident on the panels from 2261.06 kWh/m2 (in the first and second configurations) to 2251.99 kWh/m2 (in the third and fourth configurations). It is also clear from table 5 that the first and third configurations had low values of the total losses caused by the shadow, which include (Shade frequency, Module-specific partial shading, Mismatch shading, Low-light performance). In addition, the first configuration achieved the highest value of the performance ratio of the system.

Table 5: The most important technical results of simulation

	Total capacity obtained from configuration, kWp	**Total number of PV panels**	**Net generated energy injected to grid, kWh/year**	**Total losses caused by the shadow, %**	**Performance ratio of the system, %**
First configuration	51.23	94	98225	3.6	84.4
Second configuration	51.23	94	96870	4.9	83.3
Third configuration	56.68	104	108128	3.5	84.3
Fourth configuration	56.68	104	105733	5.6	82.5

Based on the technical results of the simulation obtained in the previous section, the system with the first configuration was selected in order to make economic feasibility for it using the same simulation program (PVSOL). As shown previously, the first configuration of the system has 94 panels with a total capacity of 51.23 kW and a net annual generated energy of 98225 kWh. Based on the study of the prices of components of this system in the local market and based on the global price of the cost of a kilowatt for such systems, which is estimated at about 800 $/kW, the total cost of the system with the first selected configuration can be estimated at about 40000 $ (including the cost of panels, inverter, Mounting Structures, cables, circuit breakers, protections, transportation and installation fees).

The total capacity of the selected system can cover a large part of the building's loads (all computers, lighting, other equipment) without exporting any energy to the state electric grid (Zero Export Function), which in turn will reduce the load on the state electric grid, reduce dependence on traditional resources of energy generation (fuel and gas) and their high costs, and contribute to reducing the burden on the state budget in terms of reducing part of the financial support provided to the electricity sector. While in the case of obtaining approval and license for the project from the ministry of electricity, then the generated entire or surplus energy can be sold to the transmission and distribution public state establishment of electricity at a price of 7 euro cents per kWh (based on the law № 1113 in 2020, which determined encouraging purchase prices of produced energy from renewable energy projects). Based on the above, there is an economic feasibility of the project, whether the generated energy is consumed within the building or sold to the ministry of electricity according to the encouraging prices.

Figure 7 shows the economic indicators of the system with the first configuration by assuming that: the entire generated energy from the project has been sold to the transmission and distribution public state establishment of electricity at a price of 0.07 €/kWh = 0.075 $/kWh, the project life is 25 years, the capital cost is 40000 $, the annual operation and maintenance cost is about 100 $, and the power degradation of PV panels is 0.55 %/year.

The simulation results (figure 7) show that the net income (net present value) is estimated at about 123000 $, the payback period is about six years, the internal rate of return is about 17 %, the cost of generated electric energy (levelized cost of electricity) is about 0.02 $/kWh. Therefore, the project is profitable and has economic feasibility. From the environmental point of view, this project reduces carbon dioxide emissions by about 74000 kg/year.

Economic Parameters		
Return on Assets	16.78	%
Accrued Cash Flow (Cash Balance)	122,993.88	$
Amortization Period	5.7	Years
Electricity Production Costs	0.02	$/kWh
Payment Overview		
Specific Investment Costs	780.79	$/kWp
Investment Costs	40,000.00	$
One-off Payments	0.00	$
Incoming Subsidies	0.00	$
Annual Costs	100.00	$/Year
Other Revenue or Savings	0.00	$/Year

Figure 7: Economic results of the proposed project

4. Conclusion

This work will contribute to raising awareness of the importance of implementing solar PV projects on the roofs of government buildings and the need to take advantage of the available wasted space on these roofs. Based on this study, it can roughly say that the empty space available on the roofs of all buildings (about 10 buildings) belonging to the government scientific institution (subject of the study) allows the implementation of solar photovoltaic projects with a total capacity ranging from 500 to 750 kW, which will contribute to achieving economic feasibility whether the energy is self-consumed or sold to the state ministry of electricity. The study also showed the importance of modeling and simulation programs such as the PVSOL program in conducting a simulation of any solar photovoltaic project before its implementation on the ground by studying its performance and all parameters.

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