Cost and Energy Optimization in Ground Mounted Solar Energy Power Plant Projects

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Abstract

With the increasing need for energy, all humanity is searching for new natural energy sources. The amount of fossil energy sources is decreasing worldwide, which is a threat to human health. Because of that reason, natural and renewable energy sources will alleviate this problem. Solar energy is a case in point for that problem. Before integrating solar energy sources into the national grid structure, their electrical projects should be designed carefully. Different schemes and layouts can be considered in that regard. This study explores the cost and energy optimization of solar energy projects during the design process. And the result shows that the savings from the optimized engineering design are approximately 200,000 USD. Along with the highest savings amount, the levelized cost of energy is also decreasing with a good engineering design up to 0.287 TRY.

1. Introduction

Ever since humankind has walked the earth, he has always had a need for energy and has sometimes met this need through physical strength and has sometimes figured out alternative ways. In fact, prehistoric times were not that different from our time. The only difference is that the earth was a much cleaner place. Namely, based on the current situation of our world where industrialization is the basis of our living condition, most of the need for energy is provided by power plants. While some of these can be plants that use fossil resources such as coal and natural gas, other kinds of plants that operate without any fossil fuel input to produce energy, such as solar and wind power plants [1,2]. The emission of CO2 and other poisonous gases into the environment resulting from fossil resourced energy production affects our environment diversely, brings about global warming, and humankind is forced to struggle with new kinds of ailments every passing day [3]. This is the reason why centuries ago, there existed a much cleaner world. Now, renewable energy resources like hydroelectricity, sun, wind, and biomass [4] are able to provide about 15-20% of total energy requirement throughout the world [5]. It is within our power to take this percentage higher. Currently, about 1.6 billion people live without electrical energy, and around 1.1 billion people are without a water source [6]. The use of clean energy resources primarily to assist those people that have trouble meeting their basic needs would cause humankind to lead a better and more livable life, and the percentage of renewable energy use that provide the total energy requirement would increase significantly.

Turkey has a great solar energy potential throughout the country [7]. Day by day, many solar energy projects are being realized in the southern part of the country. Projects for solar energy power plants consist of static and electrical system designs.

Equipment for the static parts is mostly made of steel, iron, and aluminum, while aluminum is also used in selecting electrical cables for projects. Designing solar projects first starts with determining the solar project area. The project area can sometimes be rooftops of industrial facilities or ground that is not used for agricultural applications. In this study, a solar project is being designed in the city of Adana. The latitude and longitude of the selected location are 36.77 ºN and 35.79 ºE.

2. Methodology

In a study, three different solar energy power plants with different module power were investigated for Kuala Lumpur, Malaysia. According to reference studies, the sizing ratio of photovoltaic (PV) power-inverters should be under 1 to avoid overload losses. In three power plant designs, PV modules consist of monocrystalline and polycrystalline cells. The installed powers of power plants are respectively 1 MW, 1.5 MW, and more than 2 MW. As the methodology for power plants, only PV modules and the size of the inverter PV modules are considered. According to these inputs, the levelized cost of energy (LCOE) values for each power plant are between 0.0380 USD/kWh and 0.0375 USD/kWh. Total energy productions for each power plant are respectively 37,263 MWh, 58,832 MWh, and 82,046 MWh. Energy losses are calculated at 8% [8].

In a master's thesis, a study is conducted for a 50 MW solar power plant in four scenarios. PVSyst and SAM solar energy software enables the realization of energy and economic analysis. Trina solar and First solar brands are utilized as photovoltaic module producers. Module technologies include polycrystalline and thin film. Sungrow and KACO solar inverters are also used for this research. To conduct a good analysis, four scenarios are created by matching both inverters to each solar module. The installed capacities of the scenarios are respectively 52.75 MWp, 53.35 MWp, 50.92 MWp, 51.83 MWp. String lengths vary depending on the open circuit voltages of the solar modules. Dirt and shading losses are added up to all cases at 10%. Annual energy injected to the grid is between 83,418 MWh and 78,069 MWh for all cases. Total capital costs are considered to be calculated using LCOE values. And capital costs vary between 46,120,000 EUR and 41,179,000 EUR. For 25 years, the cost of operation and maintenance is around 20,000,000 EUR. So, the LCOE values are between 3.11 and 3.32 cent euros per kWh [9].

In another study of 50 MW installed power for Dhaka Bangladesh, optimization was achieved by changing the tilt angles of solar modules. According to the study, the best optimization angle is 25 degrees. The project generates 82,387 MWh of energy and the payback time is 5.5 years [10] .

In another interesting study, the methodology is used for fixed tilted ground-mounted solar energy power plants. The aim of optimization is to capture the maximum amount of energy from the solar panels using an algorithm. The algorithm is used to determine the shading between solar panels. Arranging the layout of solar panels and adjusting their tilt angles can provide the optimal design for a ground-mounted system in the study. As a result, the vertical layout 2x12 configuration with a tilt angle of 30 degrees and 3x8 configuration with a tilt angle of 14 degrees generates the maximum energy [11].

3. Design of Project Cases

The chosen project's area is 34,000 square meters. And there is no slope on the ground surface. Two cases and solar placements are created to analyze the cost and energy difference between them. The portrait layout is used for both solar placement cases. In case A, the solar panel brand is HSA Energy blue pine panels with a 550-watt rated monocrystalline half-cut panel, while in case B, CW Energy 550-watt half-cut panels. Datasheet information for solar panels can be found in Table 1 and Table 2. It can be seen that HSA brand solar panels have more panel length than CW Energy solar panels. Besides the dimensions, the open circuit voltage (Voc) values of HSA solar panels are higher than those of CW Energy solar panels. Having smaller Voc values makes it possible to create long solar strings in projects.

Table 1. HSA panel datasheet information

HSA 550-Watt Solar Panel			
Voc (Volt)	***Vmp (Volt)***	***Isc (Amper)***	***Imp (Amper)***
49.90	41.96	14	13.11
Dimensions: 2279 x 1134 x 35 mm			

Table 2. CW Energy panel datasheet information

CW 550-Watt Solar Panel			
Voc (Volt)	***Vmp (Volt)***	***Isc (Amper)***	***Imp (Amper)***
37.9	31.5	18.49	17.46
Dimensions: 1965 x 1303 x 35 mm			

In case A, Solplanet 100 kW solar inverters are used, while in case B, Hopewind 250 kW solar inverters are used. Solplanet inverters have an alternative current (AC) output voltage of 400 V, while Hopewind inverters have an AC output voltage of 800 V. Beside that specifications, Solplanet inverters have maximum direct current (DC) voltage of 1100 Volt whereas Hopewind inverters have 1500 V. The string length are determined according to (1), (2), (3) seen below [12].

$$k_{1,2}=1+\frac{(\text{CT-STT}) \text{ x PVT}}{100} \tag{1}$$

$$\text{Vocstring}_{max}=k_1 \text{ x Voc}_{string} \tag{2}$$

$$\text{Vocstring}_{min}=k_2 \text{ x Voc}_{string} \tag{3}$$

Where:
CT: Correction Temperature, STT: Standard Test Temperature, PVT: Panel Voltage Temperature Coefficient for HSA is -0.275 and for CW Energy is -0.270 [12,13].

In case A, the length of the solar string is 20 whereas in case B, it is 36. Calculations are done for temperatures k1, -10 °C and k2, 70 °C. Although the cold temperature value is not seen in the Adana region, the project has safe design values. Solplanet 100 kW inverters [14] have 10 mppt inputs, and each mppt has two inputs. Hopewind 250 kW inverters [15] have 12 MPPT inputs, and each MPPT has two inputs. For a selected project area, the row distance between two arrays can be determined according to (4), (5), (6), (7), (8), and (9) [16]. Fig. 1 shows the geometry of how to calculate row distance.

$$\sin(h)=\cos(d) \text{ x } \cos(l) \text{ x } \cos(hr)+\sin(d) \text{ x } \sin(l) \tag{4}$$

$$d=23.45 \text{ x } \sin\left(\frac{360}{365} \text{ x } (n+284)\right) \tag{5}$$

$$hr=(ST-12) \text{ x } 15 \tag{6}$$

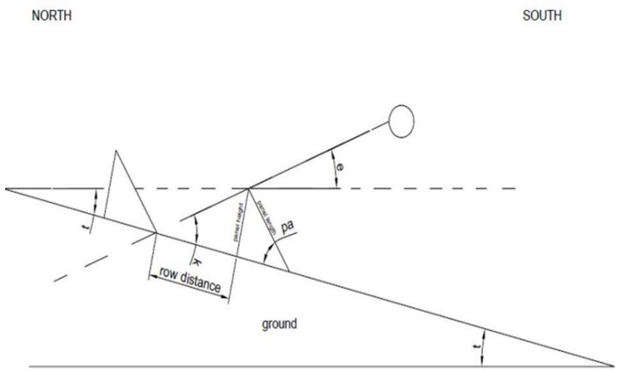

Fig. 1. Geometry of row distance of solar arrays

$$\sin(pa)=\frac{\text{panel height}}{\text{panel length}} \tag{7}$$

$$k= e + t \tag{8}$$

$$\tan(k)=\frac{\text{panel height}}{\text{row}_{distance}} \tag{9}$$

Where:
h and e: Solar elevation angle, d: Solar declination angle, l: Latitude of selected project area, hr: Hour angle, n: Day number of the year, ST: Solar time, pa: Panel inclination angle, k: Profile angle, t: Ground slope angle.

The row distance between arrays should be calculated when the sun rays come so obliquely to the world. And that time is valid for 21 of December. 21 of December which is equal to the number of the year is 355. So, the declination angle of the time is -23.45 degrees.

The hour angle is calculated when the sun rays come to the object at 12.00 solar time. So, the hour angle becomes 0. If the latitude of the area is 36.7687 and the sun elevation angle is 29.7813 degrees. For case A, solar panels that are directly facing south should be inclined to 31 degrees from the ground to maximize energy production. According to the slope of solar arrays, the panel height increases by 2,357.84 mm. The solar arrays were made in a portrait style for case A. The ground slope of 0 degrees leads to a profile angle of 29.7813 degrees. Finally, the row distance for case A is calculated as 4.12 meters.

For case B, CW Energy panels are used. To obtain more energy and optimize solar panel placement, the inclination angle of the solar panels is decreased to 21 degrees. So, the row distance of case B is calculated as 2.48 meters. Since the row distance is lower than in case A, in case B, the total number of solar panels is 6,264 whereas in case A, it is 5,840. The total power of case A is 3,212 kWp, while in case B, it is 3,445.2 kWp. AC power is 2,500 kW and 3,000 kW respectively. In case A, the total number of inverters is 25 while in case B, it is 12. With that optimization opportunity, DC cables are used at a minimum level. To calculate the DC string cable to the inverter, please refer to Fig. 2. In case A, the first panel of the string has a distance of 23.06 meters from the last panel of the string. However, in case B, the first and last solar panels will have the same final output, and there will be a savings of 23 meters from the DC string cable. In case A, there are 292 strings, while in case B, this number is 174. The total length of the DC cable in case A is 53,610 meters, while in case B, it is 24,126 meters.

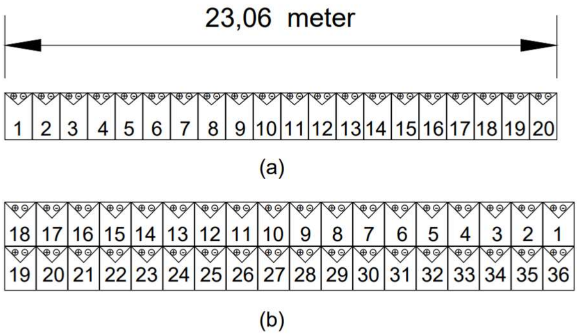

Fig. 2. Solar string cable for case A and B

Power losses from the DC cables can be calculated from (10) [17].

$$\Delta P = 2 \text{ x } I^2 \text{ x } \frac{L}{k \text{ x } q} \tag{10}$$

Where:
ΔP: Power losses, I: DC current, L: Length in meters, k: Resistivity of the DC cable, q: Cross-sectional area of the DC cable.

According to the power losses formula, case A uses 27,422 watts, while case B uses 21,889 watts. The loss percentage of the power plant in case A is 0.853 percent, while in case B, it is 0.635 percent.

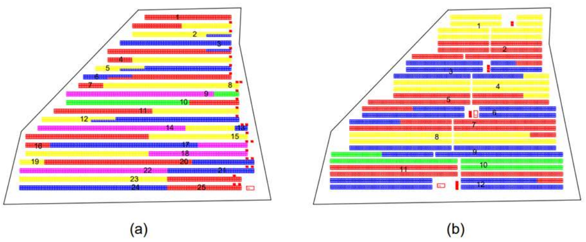

Fig. 3. Solar energy power plant placement for case A and B.

As can be seen from Fig. 3, in case A, solar inverters are located end of the strings and in case B, they are located in the centers of the strings. The inverters connected to them are represented by the colors in the panels. In addition to the DC cable optimization from case B, AC cable optimization is also being considered in that placement. The total length of the AC cables in case A is 7,896 meters and in case B, it is 4,136 meters.

AC power losses from the AC cables can be calculated from (11).

$$\Delta P_{AC} = 3 \text{ x } I^2 \text{ x } R \text{ x } L \tag{11}$$

Where:
I: AC current of the inverter, R: Resistance of the AC cable, L: Length of the inverter's AC cable.
AC current for both cases is calculated from (12) [18].

$$I_{AC} = \frac{P}{V \text{ x } \sqrt{3} \text{ x } \cos(\emptyset)} \tag{12}$$

Where:
P: Active power of the inverter, θ: Power factor of the inverter, V: Output voltage level of the inverter.
List of the power losses can be seen from the Table 3 and Table 4.

Table 3. Case A, Power losses list of AC cables

Cable Code	Length (km)	Power (kW)	Current (Amper)	Losses (Watt)	Resistance (ohm/km)
Inv-1	0.174	100	144.34	1663.8	0.153
Inv-2	0.164	100	144.34	1568.2	0.153
Inv-3	0.147	100	144.34	1727.2	0.188
Inv-4	0.140	100	144.34	1645.0	0.188
Inv-5	0.132	100	144.34	1551.0	0.188
Inv-6	0.124	100	144.34	1829.0	0.236
Inv-7	0.107	100	144.34	1578.2	0.236
Inv-8	0.110	100	144.34	1622.5	0.236
Inv-9	0.103	100	144.34	2111.5	0.328
Inv-10	0.095	100	144.34	1947.5	0.328
Inv-11	0.088	100	144.34	1804.0	0.328
Inv-12	0.081	100	144.34	1660.5	0.328
Inv-13	0.063	100	144.34	1291.5	0.328
Inv-14	0.072	100	144.34	1476.0	0.328
Inv-15	0.056	100	144.34	1148.0	0.328
Inv-16	0.045	100	144.34	922.5	0.328
Inv-17	0.049	100	144.34	1004.5	0.328
Inv-18	0.041	100	144.34	840.5	0.328
Inv-19	0.029	100	144.34	594.5	0.328
Inv-20	0.034	100	144.34	697.0	0.328
Inv-21	0.021	100	144.34	430.5	0.328
Inv-22	0.026	100	144.34	533.0	0.328
Inv-23	0.03	100	144.34	615.0	0.328
Inv-24	0.018	100	144.34	369.0	0.328
Inv-25	0.025	100	144.34	512.5	0.328

Table 4. Case B, Power losses list of AC cables

Cable Code	Length (km)	Power (kW)	Current (Amper)	Losses (Watt)	Resistance (ohm/km)
Inv-1	0.173	250	180.42	5237.3	0.310
Inv-2	0.178	250	180.42	5388.6	0.310
Inv-3	0.058	250	180.42	1755.8	0.310
Inv-4	0.063	250	180.42	1907.2	0.310
Inv-5	0.068	250	180.42	2058.5	0.310
Inv-6	0.015	250	180.42	454.1	0.310

Inv-7	0.139	250	180.42	4208	0.310
Inv-8	0.142	250	180.42	4298.8	0.310
Inv-9	0.008	250	180.42	242.1	0.310
Inv-10	0.011	250	180.42	333.0	0.310
Inv-11	0.014	250	180.42	423.8	0.310
Inv-12	0.015	250	180.42	454.1	0.310
TR	0.150	1500	25.10	110.3	0.389

Beside of the inverter output voltage of 800 V is higher than case A and aluminum conductors are used in case B. In that aspect, power losses of all inverters in case A are 31,143 watts whereas in case B, is 26,872 watts. Power losses percentages in AC cables for both cases A and B are respectively 1.24 percent and 0.89 percent.

In case A, first two inverters have AC cables of 150 mm², following three inverters' cables are 120 mm², three inverters more have 95 mm² cables, and rest of all is 70 mm², and all cables have copper conductors. In case B, all inverter cables are made of aluminum conductors and have cross-sectional areas of 120 mm². In case B, there is a single transformer collecting the power of the first 6 inverters and transmitting it at a 34.5 kV voltage level to the main distribution unit. Because of the usage of the transformer like that, it makes more savings on cable lengths.

4. Results of Project Cases

Costs of both cases can be seen in Table 5 and Table 6. For the case A, having HSA branded solar panels consists of 3,212 kWp solar power with the 0.69 cent USD per wattage whereas in case B, 0.63 cent USD per wattage for 3,445.2 kWp power plant. The exchange rate is 26.71 USD/TRY.

The costs considered to not change for both cases are grounding and earthing equipment, transformers and transmission units, supervisory control and data acquisition (SCADA), measuring units, and engineering.

Table 5. Case A, list of costs

Equipment	Quantity	Unit Price (USD)	Total Price (USD)
Solar Panel	3,212,000 Watt	0.40	1,284,800
Inverters -100 kW	25	4,075	101,875
Construction	3,212,000 Watt	0.075	240,900
70 mm² NYY	3,504 meters	7.65	26,805.60
95 mm² NYY	1,364 meters	10.50	14,322.00
120 mm² NYY	1,676 meters	13.34	22,357.84
150 mm² NYY	1,352 meters	16.36	22,118.72
Busbar 2500 A.	2 set	17,312	34,624.00
DC cable 6 mm²	53,610 meters	1.20	64,332.00
Earthing 35 mm²	2,000 meters	5.90	11,800.00
CAT 6 cable	250 meters	0.20	50
Low voltage panel	2 set	15,000	30,000.00
Earthing strip	1,500 meters	1.30	1,950.00
Earthing rod	20	50	1,000.00
Lightening	1 set	7,500	7,500.00
Transf. and Units	1 set	250,500	250,500.00
Connection Equi.	1 set	16,168	16,168.00
SCADA	1 set	5,500	5,500.00
Transportation	1 set	10,000	10,000.00
Installation	1 set	60,000	60,000.00
Engineering	1 set	10,000	10,000.00
Total			2,216,603.16

Table 6. Case B, list of costs

Equipment	Quantity	Unit Price (USD)	Total Price (USD)
Solar Panel	3,445,200 Watt	0.40	1,378,080.
Inverters -250 kW	12	5,300	63,600.00
Construction	3,445,200 Watt	0.075	258,390.00
120 mm² NAYY	3,536 meters	1.93	6,824.48
95 mm² XLPE-AL	450 meters	6.00	2,700.00
Busbar 1600 AL.	2 set	6,060	12,120.00
DC cable 6 mm²	24,126 meters	1.20	28,951.20
Earthing 35 mm²	2,000 meters	5.90	11,800.00
CAT 6 cable	250 meters	0.20	50
Low voltage panel	2 set	10,000	20,000.00
Earthing strip	1,500 meters	1.30	1,950.00
Earthing rod	20	50	1,000.00
Lightening	1 set	7,500	7,500.00
Transf. and Units	1 set	250,500	250,500.00
Connection Equi.	1 set	15,696	15,696.00
SCADA	1 set	5,500	5,500.00
Transportation	1 set	17,000	17,000.00
Installation	1 set	70,000	70,000.00
Engineering	1 set	10,000	10,000.00
Total			2,161,661.68

It can be seen that total cost difference between two cases is 54,941.48 USD and case B is lower than case A. To calculate the LCOE value for both cases, the consumption cases with day and peak hours is integrated to PVSyst solar software. The rates of economic parameters such as inflation, discount, income tax, and annual tariff variation are respectively 25%, 25%, 40%, and 65%. According to these inputs, the payback period and LCOE for case A are 4.2 years and 3.317 TRY/kWh, while for case B, it is 4.0 years and 3.030 TRY/kWh.

It is obvious that using aluminum cables instead of copper and preferring high-voltage inverters instead of 400 V inverters can make companies so much profit. Besides that, the inclination angle of solar panels should be optimized to obtain more power and energy in a selected project area. In this project, the inclination angle has been reduced to 21 degrees. The orientation of the solar inverters should be centered in the project area, and half of the power should be transmitted with medium voltage levels.

According to simulation results from the PVSyst solar software, the total energy produced in case A is 5,375,021 kWh, while in case B, it is 5,743,165 kWh. When comparing the cumulative profit to case B, in case A, it is 23,142,028,394 TRY, while in case B, it is 23,509,519,886 TRY. The engineering in the case B shows the power with the net present value (NPV) over the project lifetime.

5. Discussion and Conclusion

In previous works and research, optimizing can only be achieved by changing the panel and inverter brand since they have different technical specialties. But this study shows that optimizing a system cannot be done alone by changing panels or inverters in each other. The project layout is also handled by a project designer. In this project, a layout is drawn using two different solar modules. And the location of the inverters also differs from each case. Since the placement of inverters to obtain the minimum cable length is reducing project costs significantly. In other previous works, the design criteria both for reducing costs and maximizing energy were not clearly visible.

Second important thing of this project, using high voltage both for inverters' output and distribution panel, decreases the voltage and power losses and allows to carry high powers in the long distances.

Another important point that has similarities with previous work is managing the tilt angle. In other studies, the tilt angle is only fixed to maximize the energy from the solar panels. However, in our study, the tilt angle can be decreased to achieve a minimum shadow length and increase the placement of solar panels in the project area.

For future works, an optimization study should be analyzed since solar panel dimensions are changing day by day. That leads to a decrease in the use of solar modules in project areas. And more efficient systems can also be achieved.

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