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Design and Simulation of a Solar Powered House in Muğla: Roof Decorated with Half Cut Cells

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ABSTRACT

In this article, the performance, design and efficiency calculation of photovoltaic systems were made using PvSol program for a house in Muğla. For roof type panel design close to standard installations, panel position and panel type were designed based on Muğla province sun hour data and roof shading factor. In this study, the data obtained for the roof type installation designed in Muğla city using monocrystalline, polycrystalline and half-cut monocrystalline cells were compared. When yield, area and price parameters were compared, it was found that the best cell type was half-section monocrystalline. As a result of the simulations, it was found that the average daily energy need of the house was 6.4kWh, fed by 14 half-section monocrystalline panels. The results obtained are consistent with the data in the literature.

Muğla'da Güneş Enerjili Bir Evin Tasarımı ve Simülasyonu: Yarım Kesim Hücrelerle Kaplanmış Çatı

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ÖZ

Bu makalede, fotovoltaik sistemlerin performansı, tasarımı ve verim hesabı, Muğla’da bulunan bir ev için, PvSol programı kullanılarak yapılmıştır. Standart kurulumlara yakın çatı tipi panel dizaynı, panel konumunu ve panel çeşidini Muğla ili güneşlenme saat verilerine ve çatı gölgelenme faktörüne dayalı olarak tasarlanmıştır. Yapılmış olan çalışmada, monokristal, polikristal ve yarım-kesim monokristal hücreler kullanılarak tasarlanan çatı tipi kurulum için elde edilen veriler karşılaştırılmıştır. Verim, alan, fiyat parametreleri karşılaştırıldığında en iyi hücre çeşidinin yarım-kesim monokristal olduğu bulunmuştur. Yapılan simülasyonlar sonucunda, evin ortalama günlük 6,4kWh’lık enerji ihtiyacının 14 adet yarım-kesim monokristal panel ile elde edildiği sonucuna varılmıştır. Elde edilen sonuçlar literatürdeki verilerle örtüşmektedir.

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1. Introduction

Energy is by far the most important requirement and universally accepted indispensable part of life on earth. That is the reason why so many researchers are working on the energy concept. Energy, which can be found in many forms, is mainly divided into two categories: Renewable and non-renewable sources (Güven and Atalay, 2018). Non-renewable energy sources, such as coal, nuclear, natural gas and oil, are available with limited resources. When coal, natural gas and oil are used to generate energy, they emit heat-trapping gases like carbon dioxide (CO_2). This process of trapping heat causes climate change, and failure to address this problem accelerates current global warming. Fossil fuels made up of the remains of ancient living organisms contain hydrocarbons such as gas and coal. These energy sources cause greenhouse gases and very harmful chain reactions. The emerging heat caused by greenhouse gas and global warming causes water scarcity and endangers life. Unlike non-renewable energy sources, renewable alternatives are given us by nature freely, and in addition to that they are environmentally friendly. The advantages of renewable energy sources are numerous and affect the environment and life of all living things. As shown in Figure 1, sun, wind, hydro, and geothermal can be given as the main examples of the most basic renewable energy resources (Alrikabi, 2014).

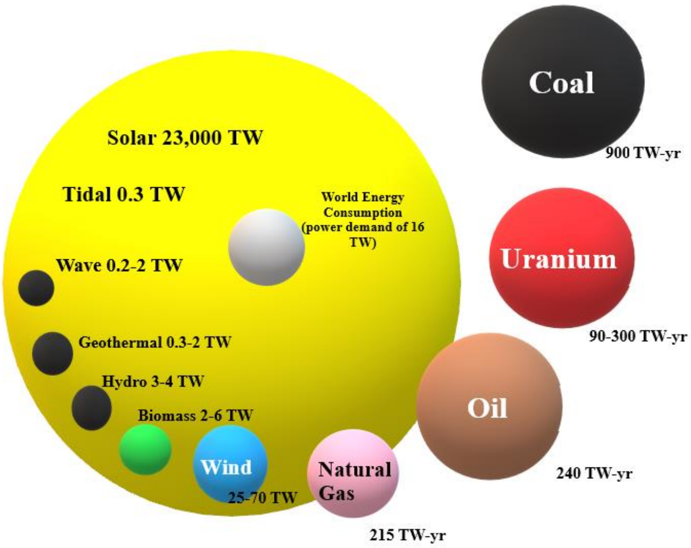

Figure 1. Global energy potential (Uslu, 2016)

Among the given resources, solar energy is the one with the highest potential. In order to be able to use this potential we have to convert the sun's energy into electrical energy. The conversion process, which is called Photovoltaic (PV) technology, is achieved with solar cells. Photo means "light" and voltaic means "electricity", which generates electricity directly from sun light by means of the PV effect. PV cells are made of semiconductors, and have electric fields that force electrons freed by light absorption to flow in a certain direction. This flow of electrons is an electric current; when the metal contacts are placed on the top and bottom of the PV cells, it allows us to draw the current off for external use (Demiryürek et al., 2020). The majority of solar cell technology, especially first-generation solar cells, has been based on the most abundant semiconductor element Silicon (Si) (Mandong and Üzüm, 2019). The basic schematic of a crystalline Si (c-Si) solar cell can be seen in Figure 2.

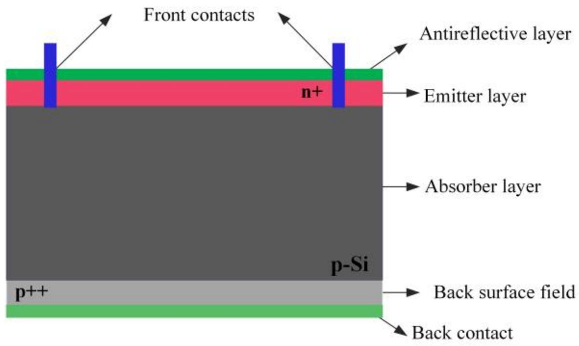

Figure 2. Schematic of c-Si based solar cell

Thanks to the developing technology, it has been possible to work with different types of cells. A single solar cell cannot generate enough amount of energy required for households or buildings. To increase the output of energy in terms of electricity, PV cells are electrically connected together. It is called a PV module. These modules are connected to form a panel/array. The required number of modules is connected to form an array depending on the consumption of the house or building. Basically, with the connection of the cells, modules are obtained, in other words, panels, and with the connection of the modules we end up with the arrays as depicted in Figure 3.

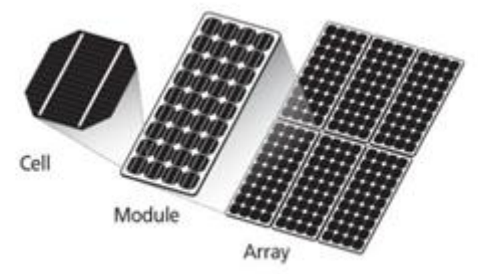

Figure 3. The representation of a basic notation that goes from simple to complex: cell, module, array (Adak et al., 2018)

In this paper, we have focused on three types of cells: Monocrystalline (mono-c), polycrystalline (poly-c) and half-cut mono-c. Mono-c and poly-c panels are generally made of 60 or 72 cells but half-cut arrays are made of 120 or 144 cells (Duman and Alçı, 2022). Half-cut cells are literally normal solar cells that have been cut in half. The aforementioned module types are used in PV systems, they all have different physical and electrical properties. Depending on their properties, limits, fabrication technologies and finally installation stage, one can select the best option. The best option is defined with the cost and effectiveness.

2. Materials and Method

2.1. Theoretical Study on Solar Cells and Their Working Principle

Solar radiation, in other words, sunlight, is a general term for the electromagnetic radiation emitted by sun. Solar radiation, whose spectrum is given in Figure 4, can be turned into useful forms of energy, like electricity.

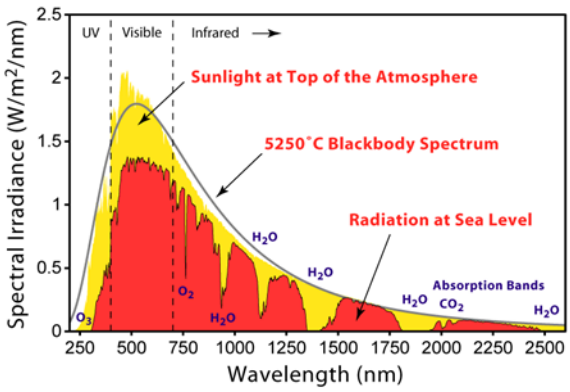

Figure 4. Solar radiation spectrum (Penn State, 2020)

The solar spectrum, consisting of and depending on different wavelengths, is defined as both particles and waves. Particle-wave duality affects the interaction of sunlight with the material. The interaction can be basically divided into three groups: a) reflection, b) transmission, and c) absorption as shown in Figure 5.

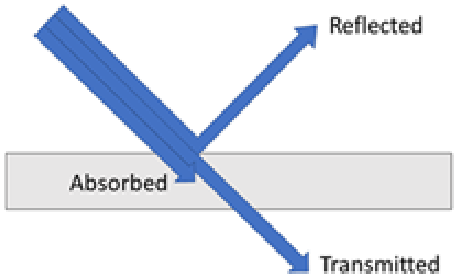

Figure 5. The schematic view of the reflected, transmitted, and absorbed light

For PV systems the higher the absorption, the higher the efficiency is. The sunlight absorption by a solar cell is the process in which light is absorbed by the cell and converted into energy. The energy produced is direct current (DC) and the inverter converts the DC form into the alternating current (AC). If the intensity of the light increases, the total absorption will increase so as the efficiency (Adak et al., 2021).

There are different types of PV cells which are made up of semiconductors having conductivity between conductors and insulators to interact with incoming photons from the sun. Semiconductor material that is composed of a single type of element, is known as intrinsic. It is actually quite common to find semiconductors that contain impurities or atoms of more than one kind, which is called extrinsic. Impurities are added to a semiconductor to increase the electrical conductivity. The process of adding an impurity into the semiconductor to increase its ability to conduct electricity is known as doping (Schubert, 1993). There are two types of doping process: p-type and n-type. After the doping process, we can end up with a p-n junction, where the current flow will start towards the contacts upon the interaction of the cell with the light as depicted in Figure 2.

Altering the electrical property of the material is required, but not enough for highly efficient solar cells. In order to end up with highly efficient solar cells we must consider both electrical and optical point of view. For the electrical view, the doping amount, the physical design of the cell, in terms of junction depth, front and back contact distance to the junction should be carefully optimized. For the optical view, as explained before, the absorption amount should be maximized in order to maximize the interaction of the incoming beam with the cell (Abenante, 2006).

2.2. Types of Solar Cells

With the development of technology over time, many types of solar cells have been produced (Liu and Hou, 2014). In this work, we have investigated: mono-c, poly-c, and half-cut mono-c. We compared the characteristics of the panels to select the most suitable type for this research. The summary of the current studies in the literature in terms of cost, efficiency, and lifespan is tabulated in Table 1.

Table 1. Types of solar cells

Types of Panels	Mono-c	Poly-c	Half-cut Mono-c
Cost for one panel	160 $	85.5 $	191.1 $
Efficiency	17%- 20%	13%- 16%	Over 20%
Lifespan	25+ years	25+ years	25+ years
Aesthetics	Black Hue	Blue-Ish Hue	Half-Cut Black Hue
Annual Degradation	1% per year	0.7% per year	0.55% per year
CO_2 Emissions avoided	5.000 kg/year	4.964 kg/year	5.138 kg/year
Yield reduction due to shading	5.3 %/Year	4.7 %/Year	1.3 %/Year

The price information was taken from CW Energy Company Website (CW Energy, 2023). According to the taken price information, the watt peak price of one panel can be seen in Table 2.

Table 2. Watt peak price for mono-c, poly-c and half-cut mono-c

Type of Panels	Watt*Watt Peak Price	Price
Mono-c	400W*0.40 $	=160 $
Poly-c	285W *0.30 $	=85.5 $
Half-Cut Mono-c	455W*0.42 $	=191.1 $

2.3. Solar Energy in Muğla

In this work, we have selected the location of the house in Muğla and south direction. The reason for this choice was to be able to make comparison based on actual application results. South is known to be the best direction for solar panels due to the interaction between sunlight during both sunset and sunrise. Panels on a standard pitch roof facing to the north are known to end up with roughly 30% less efficiency values than south. Despite the fact that 25-30% less production is made compared to the south side, if there is a roof facing north-south and if the angle of the panels is between 5-7 degrees, panel settlement is made on the north side. If the facade of the house does not face south, settlement can be made on the east-west side. The east-west side produces 4-5% less energy than the south side. At sunrise, the panels on the east side produce more energy than the west side, whereas at sunset the panels on the west side produce more than the east side as shown in Figure 6 (Solar Design Guard, 2023).

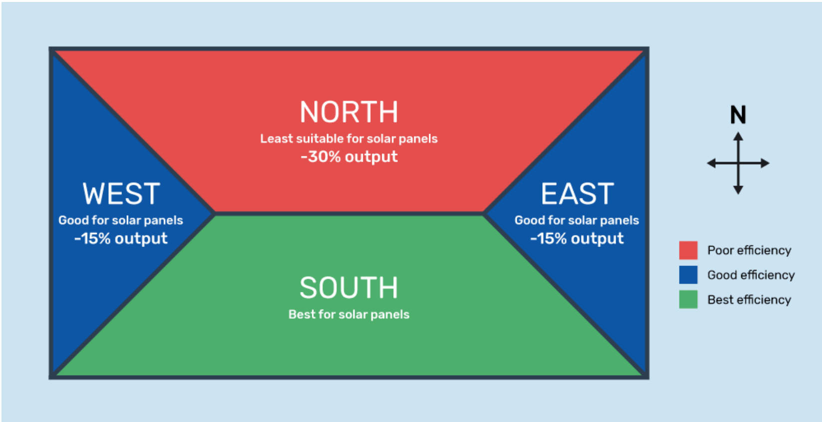

Figure 6. Face directions of the solar panels (Solar Reviews, 2023)

If the location changes, sunshine hour (a sunshine hour is a climatological term, measuring the duration of sunshine in a given period for a given location on Earth) also changes. Table 3 summarizes the different locations with different sunshine hour. The data for Muğla city was obtained from PV geographical information system as given in Figure 7 (Photovoltaic Geographical Information System, 2023).

PV technology:	Crystalline silicon
PV installed [kWp]:	1
System loss [%]:	14
Simulation outputs:	
Slope angle [°]:	35
Azimuth angle [°]:	0
Yearly PV energy production [kWh]:	1607.09
Yearly in-plane irradiation [kWh/m^2]:	2147.6
Year-to-year variability [kWh]:	32.76
Changes in output due to:	
Angle of incidence [%]:	-2.52
Spectral effects [%]:	0.19
Temperature and low irradiance [%]:	-10.9
Total loss [%]:	-25.17

Figure 7. Yearly PV energy production for Muğla

We have calculated the sunshine hour for Muğla as:

$$\text{Daily average PV energy production for Muğla} = \frac{\text{Yearly PV energy production for Muğla}}{\text{Day}} \tag{1}$$

$$\frac{1607.09\ \text{kWh}}{365} = 4.4\ \text{kWh}$$

Table 3. Sunshine hour for different provinces (Photovoltaic Geographical Information System, 2023)

Province	Sunshine Hour
Muğla	4.4 kWh
Ankara	3.9 kWh
Diyarbakır	4.08 kWh
İzmir	4.28 kWh
Hatay	4.26 kWh
Trabzon	2.78 kWh
Edirne	3.82 kWh

To sum up, if the location changes, not only sunshine hour will change, but also the interaction between panels and sun, as a result efficiency, will change.

2.4. PvSol Design

PvSol is a simulation program with 3D visualization and detailed shading analysis for the calculation of PV systems (PvSol, 2023). The user-friendly program provides a combination of appliances, battery systems, and electric vehicles. With PvSol we have designed and simulated different types of solar cells.

The consumption power of all electronic devices used in the house was calculated and the need of the house was found. Depending on our calculations, the monthly consumption power of the house was found as 883170 W.

$$\text{The daily consumption power of the house} = \frac{\text{The monthly consumption power}}{\text{Day}} \tag{2}$$

$$\frac{883170 \text{ W}}{30} = 29 \text{ kW}$$

$$\text{The required amount for the installation} = \frac{\text{The daily consumption power of this house}}{\text{Daily average PV energy production for Muğla}} \tag{3}$$

$$\frac{29\text{kW}}{4.4\text{kWh}} = 6.4 \text{ kWp}$$

As regards to these results, it was found that the required amount for the installation was 6.4 kWp.

2.5. PvSol Design with Mono-c Panels

In order to provide the required energy amount of 6.4 kWh, we have selected 400 Wp PV mono-c panel from CW Energy Company, which is a wholesaler and distributor of solar panels (CW Energy, 2023) and then we calculated the number of panels needed for this power.

$$6400W\text{p} \div 400W\text{p} = 16 \text{ (number of panels)}$$

We have used 16 mono-c panels and one inverter on the rooftop. The produced current type is in DC form, and with the help of an inverter, it is converted into AC form that can be used in houses, workplaces, etc. In addition to the required energy amount, all the risk parameters have been considered, like shading (Bimenyimana et al., 2017). In order to reduce this shadowing effect, we preferred to split Maximum Power Point Tracking (MPPT) in half. At sunrise, due to the length of the house's chimney, and at sunset the satellite has made shading on the panels. After arranging the panel placement, we have examined the shading effect as shown in Figure 8.

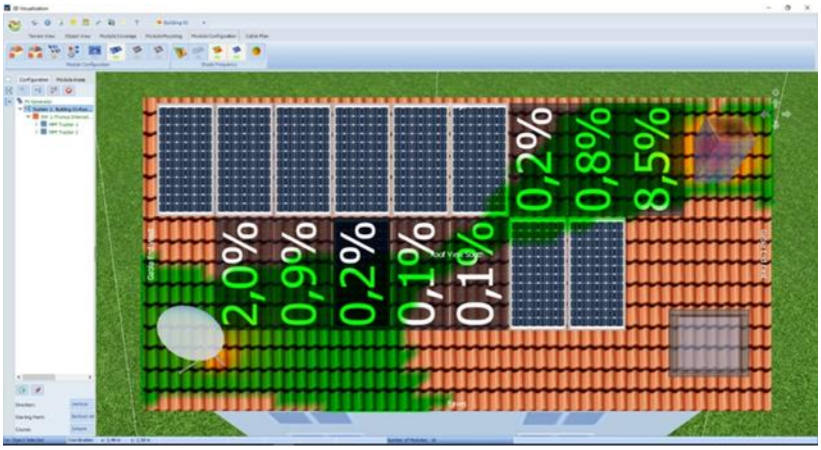

Figure 8. Shading on mono-c panels

If we have used a single and serial connected MPPT, the efficiency would decrease at sunrise and sunset. To minimize the shadowing effect, we have split the MPPT into two as MPPT1 and MPPT2 as shown in Figure 9.

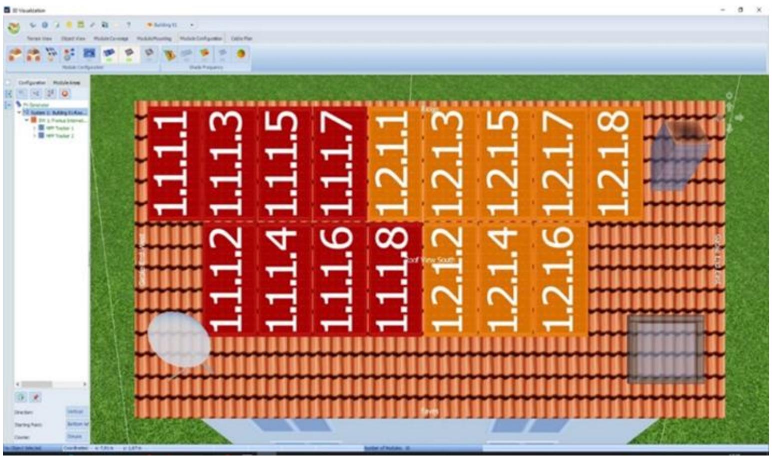

Figure 9. MPPT1 and MPPT2 for mono-c panels

After arranging the optimum position, we have placed the cables from the automatic cabling section. Wires/cables have played an important role in observing the best performance from an electrical system. Finally, the panels were placed as depicted in Figure 10.

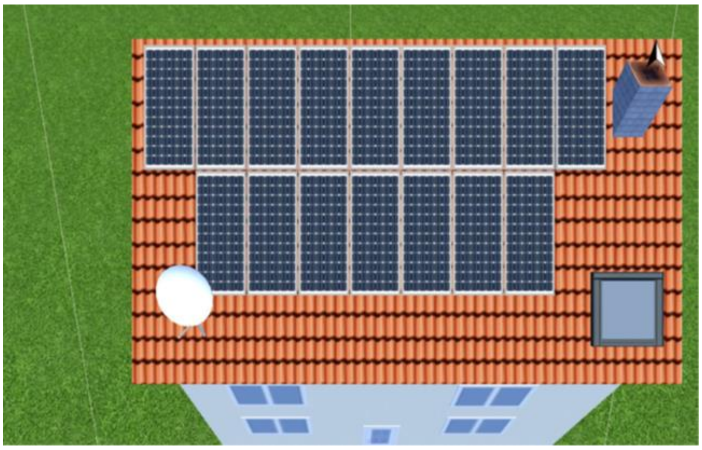

Figure 10. General view of the optimum positions for mono-c panels

2.6. PvSol Design with Poly-c Panels

We have selected 285 Wp poly-c solar panels from CW Energy Company (CW Energy, 2023) and then we have calculated the number of panels for the required power.

$$6400 \text{ Wp} \div 285 \text{ Wp} = 22 \text{ (number of panels)}$$

Depending on the structural properties of poly-c panels and the reported results in the literature, it can be said that the efficiency of poly-c panels is lower than the mono-c panels (Jiang et al., 2020). As a result of this, unlike other designs, a greater number of panels was required and the design covered more area on the roof.

As well as in mono-c panel design, shading effect and MPPT design have been made in this poly-c design. The shading effect of the poly-c covered roof, MPPT splitting, and general view of the roof obtained with PvSol can be seen in Figure 11, Figure 12 and Figure 13 respectively.

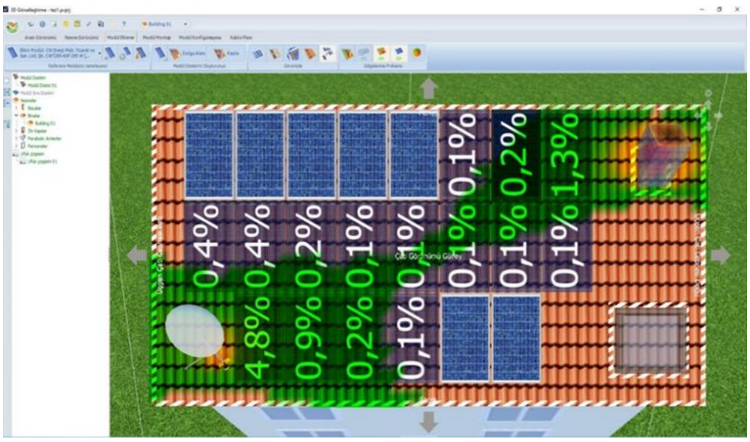

Figure 11. Shading on poly-c panels

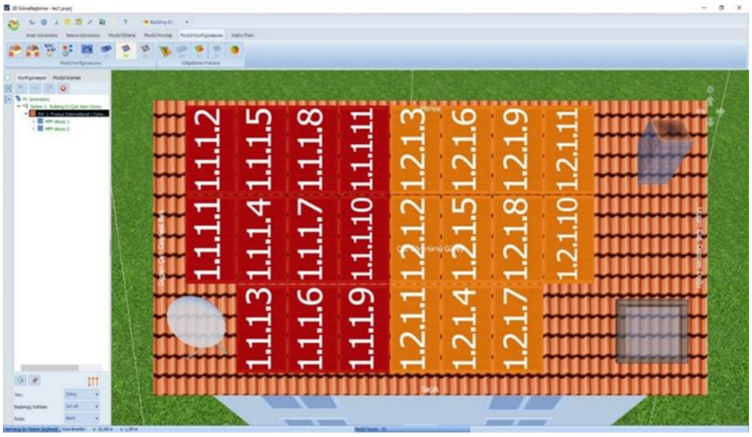

Figure 12. MPPT1 and MPPT2 for poly-c design

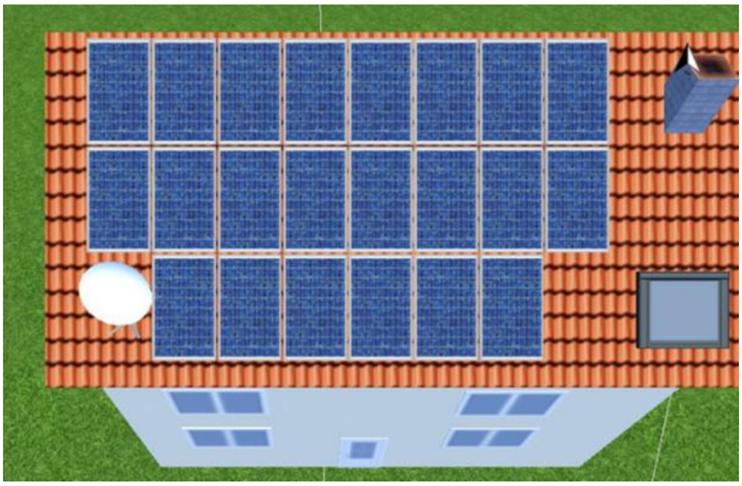

Figure 13. General view of the roof entirely covered with poly-c panels

2.7. PvSol Design with Half-Cut Mono-c Panels

We have selected 455Wp half-cut mono-c solar panel from CW Energy Company (CW Energy, 2023). The number of half-cut panels that we have used to produce this energy was calculated as follows:

$$6400\text{Wp} \div 455\text{Wp} = 14 \text{ (number of panels)}$$

Since the half-cut mono-c panels can produce higher energy compared to the other panel types, we have used less number of half-cut mono-c panels (Kewte, 2023). After simulating several alternatives, the best positioning for the panels have been selected. As done for mono-c and poly-c panel designs, also for this case the shadowing effect was investigated as shown in Figure 14. Thanks to the less number of panels, different from the aforementioned types, the shadowing effect has not dropped the output that much. To minimize the shadowing effect and to get the maximum efficiency, we have divided the MPPT in half as shown in Figure 15.

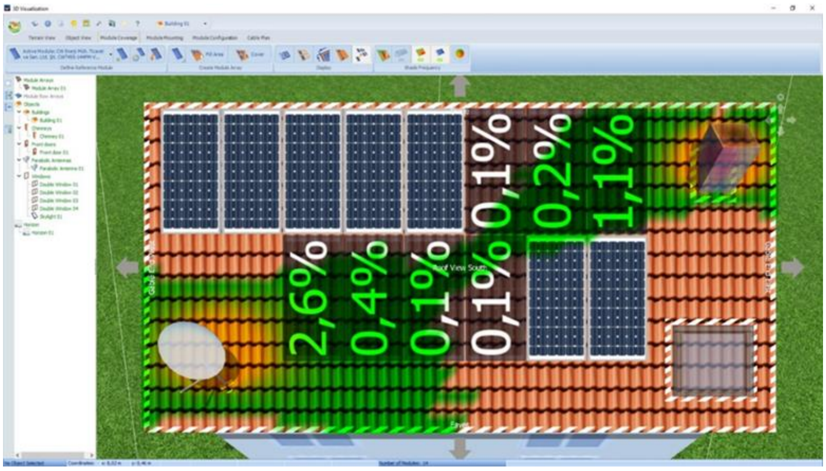

Figure 14. Shading on half-cut mono-c panels

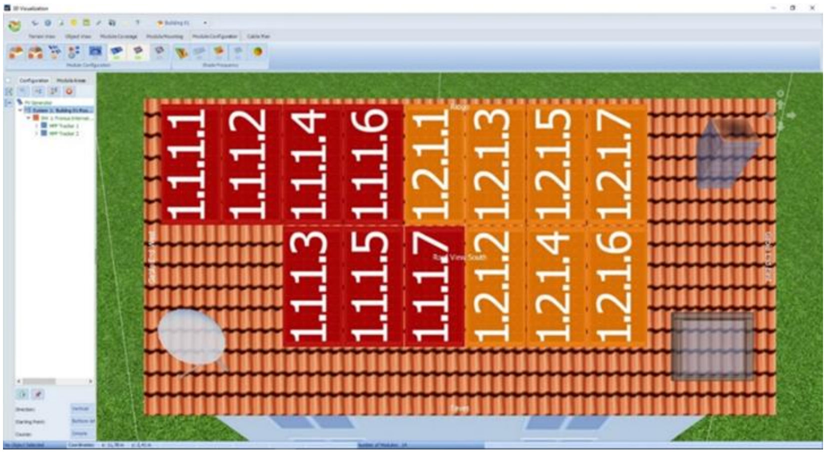

Figure 15. MPPT1 and MPPT2 for half-cut design

Unlike mono-c and poly-c type designs, the half-cut mono-c panels covered the smallest area as shown in Figure 16. The reason for this is that, as explained before, half-cut panels produce more energy than other panel types as summarized in Table 4.

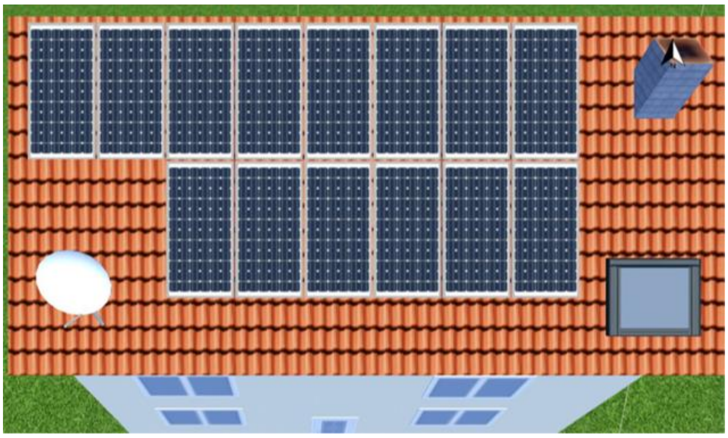

Figure 16. General view of the roof covered with half cut mono-c panels

3. Results and Discussion

3.1. Simulation Results and Comparison of Different Panel Types

According to the physical properties and the maximum energy that the panel types can produce, the number of required panel number was calculated, which is consistent with the results reported in the literature (Duman and Alçı, 2022). Half-cut mono-c panels have the highest efficiency and as a result of this high output, the number of required panel number was lower, as expected. The results of our simulation study can be summarized as tabulated in Table 4.

Table 4. The summary of our simulation study based on different panel types

Types of Panels	Mono-c	Poly-c	Half-cut Mono-c
Number of PV modules	16	22	14
Number of inverters	1	1	1
PV generator energy	10.639 kWh	10.607 kWh	10.932 kWh
Grid feed-in	10.639 kWh	10.607 kWh	10.932 kWh
Spec. annual yield	1.662,33 kWh/kWp	1.684,58 kWh/kWp	1.716,14 kWh/kWp
Performance ratio	82.90%	84.10%	85.7%
Yield reduction due to shading	5.3 %/Year	4.7 %/Year	1.3 %/Year
CO_2 emissions avoided	5.000 kg/year	4.964 kg/year	5.138 kg/year
PV generator surface	32 m^2	36.1 m^2	30.5 m^2
PV generator output	6.4 kWp	6.27 kWp	6.4 kWp
Cost for one panel	160 $	85.5 $	191.1 $

It was found that the best among other panel types was the half-cut mono-c. Half-cut panels have been recently preferred more and more, day by day (Khan et al. 2023). The amount of use has been increasing recently. It is a new technology resulting with high efficiency values. The reason of the better performances compared to other panel types is the decrease in cell's resistance based on structural facts (Duman and Alçı, 2022).

One of the main benefits of renewable energy is that it generates significantly lower CO_2 emissions than non-renewable sources (Arif, 2013). Half-cut panels can prevent more CO_2 than mono-c and poly-c as shown in Table 4. Using Equation 4, CO_2 factor for different countries and different panel types were calculated as shown in Table 5 and Table 6 respectively (Solar Blog by Kerem Çilli, 2022).

CO_2 (kg) = kWh generated energy x CO_2 factor (g/kWh) (for Turkey: 619.8 g/kWh) (4)

Table 5. CO_2 factor table by different countries

Country	CO_2 Factor (g/kWh)
USA	689.56
Japan	450
Turkey	619.8
Spain	265.4

Table 6. CO_2 (kg) values for different types of panels

Types of Panels	Mono-c	Poly-c	Half-cut Mono-c
Calculated value	5.000 kg/year	4.964 kg/year	5.138 kg/year

Upon comparing the simulation results with the studies in literature, it can be concluded that maximum CO_2 emissions avoided can be observed with the half-cut mono-c panels as shown in Figure 17.

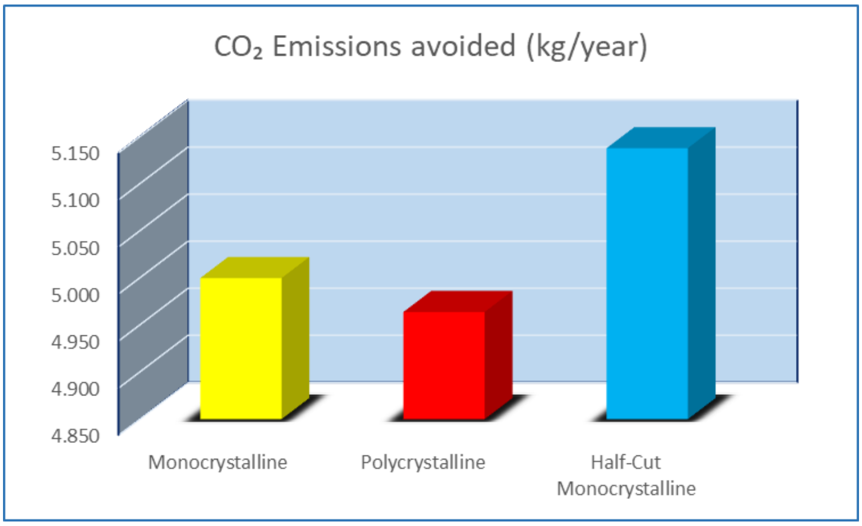

Figure 17. CO_2 emission data for different panel types

4. Conclusion and Future Work

In this paper we have presented the results of our simulation studies made for a house located in Muğla, using PvSol program. Based on the actual consumption of the designed house, the daily energy requirement was calculated and taken as 6.4 kWp. According to the real consumption amount and the physical properties of the house, such as shadowing, roof area, the location, three different panel types were investigated and analyzed, as explained in Table 4. As regards to the simulation outcomes, it was found that the optimum results, with the highest efficiency, were obtained with a roof decorated with half-cut monocrystalline panel type. This panel type has the lowest CO_2 emission amount. In addition to minimizing CO_2 emission, the smallest area coverage could be managed with half-cut panel type. For a house located in Muğla, the fourth rainiest province in Turkey, the optimum panel selection was proved to be the half-cut monocrystalline panel type, which is compatible with the real application examples. As a future work, the results will be updated and implemented depending on the energy requirement of either a house, or a factory.

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Statement of Conflict of Interest

The authors have declared no conflict of interest.

Author's Contributions

The contribution of the authors is equal.

Abbreviations

PV: Photovoltaic

CO_2: Carbon Dioxide

Mono-c: Monocrystalline

Poly-c: Polycrystalline

DC: Direct Current

AC: Alternating Current

Si: Silicon

c-Si: Crystalline Si

MPPT: Maximum Power Point Tracking

References

Adak S., Cangi H., Yılmaz AS. Mathematical model for computing output voltage of pv solar module dependent on temperature and irradiance. International Journal on Mathematic, Engineering and Natural Sciences 2018; 2(2): 124-138.

Adak S., Cangi H., Eid B., Yılmaz AS. Developed analytical expression for current harmonic distortion of the PV system's inverter in relation to the solar irradiance and temperature. Electrical Engineering 2021; 103: 697-704.

Alrikabi NMA. Renewable energy types. Journal of Clean Energy Technologies 2014; 2(1): 61-64.

Bimenyimana S., Asemota GNO., Kemunto MC., Li L. Shading effects in photovoltaic modules: simulation and experimental results. 2nd International Conference on Power and Renewable Energy, 20-23 Sept. 2017: 904-909.

Bolat M., Arifoğlu U., Demiryürek HK. Analysis of lebit energy solar power plants with pvsyst program. BEU Journal of Science 2020; 9(3): 1351-1363.

CW Energy. https://cw-enerji.com/tr/index.html (Access date: 17.05.2023)

Duman S., Alçı M. Investigation of the parameters affecting the total efficiency of solar energy panels designed with half and full photovoltaic cells. Niğde Ömer Halisdemir University Journal of Engineering Sciences 2023; 11(3): 592-600.

Güven Ş., Atalay O., Use of the renewable energy resources in Turkey. The Eurasia Proceedings of Science, Technology 2018; 4: 167-170.

Jiang L., Cui S., Sun P., Wang Y., Yang C. Comparison of monocrystalline and polycrystalline solar modules. IEEE 5th Information Technology and Mechatronics Engineering Conference, 12-14

June 2020: 341-344.

Joshi A., Khan A., SP A. Comparison of half-cut solar cells with standard solar cells. Advances in Science and Engineering Technology International Conferences, 26 March-10 April 2019: 1-3.

Kewte S., Kewte GS. Performance evaluation of 445 wp half cut monocrystalline solar panel with 380wp mono crystalline and 330wp polycrystalline solar panel for partially shading effect. Third International Conference on Advances in Electrical, Computing, Communication and Sustainable Technologies, 5-6 January 2023: 1-5.

Liu J., Hou R. Solar cell simulation model for photovoltaic power generation system. International Journal of Renewable Energy Research 2014; 4(1): 49-53.

Mashail SA. Residential solar panels and their impact on the reduction of carbon emissions. Rep Berkeley University of California 2013: 1-18.

PenneState. https://www.e-education.psu.edu/meteo300/search/node/solar%20spectrum (Access date: 15.05.2023)

Photovoltaic Geographical Information System, https://re.jrc.ec.europa.eu/pvg_tools/en/ (Access date: 15.05.2023)

PvSol. https://pvsol.software/en/ (Access date: 18.05.2023)

Schubert EF. Doping in III-V semiconductors. Cambridge University Press: New Jersey; 1993.

Solar Blog by Kerem Çilli, https://www.keremcilli.com/ (Access date: 16.09.2023)

Solar Design Guard. https://solardesignguide.com/solar-panel-tilt-and-azimuth/ (Access date: 16.09.2023)

Solar Reviews. https://www.solarreviews.com/blog/best-direction-orientation-solar-panels (Acces date: 16.09.2023)

Uslu YD. Green energy in Turkey. Kastamonu Üniversitesi İktisadi ve İdari Bilimler Fakültesi Dergisi 2016; 12: 384-392.

Üzüm A., Mandong A. Analysis of silicon solar cell device parameters using pc1d. Sakarya University Journal of Science 2019; 23(6): 1190-1197.