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Design and Comprehensive Simulation of 5 MWp and 10 MWp Solar Power Plants in Ma'an: Detailed System Design, Economic Returns, and Environmental Benefits in a Semi-Arid Climate

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Anahtar Kelimeler

Yenilenebilir enerji
Güneş enerjisi
Enerji sürdürülebilirliği
Ekonomik analiz

Graphical/Tabular Abstract (Grafik Özet)

This study encompasses the design and simulation of two solar power plants with a capacity of 5 MWp and 10 MWp, respectively, in Ma'an, Jordan. Additionally, the study evaluated the reduction in greenhouse gas emissions and the economic benefits of the solar power plant./Bu çalışma, Ürdün'ün Ma'an kentinde sırasıyla 5 MWp ve 10 MWp kapasiteli iki güneş enerjisi santralinin tasarımını ve simülasyonunu kapsamaktadır. Çalışma aynı zamanda sera gazı emisyonlarındaki azalmayı ve güneş enerjisi santralinin ekonomik faydalarını da değerlendirmektedir.

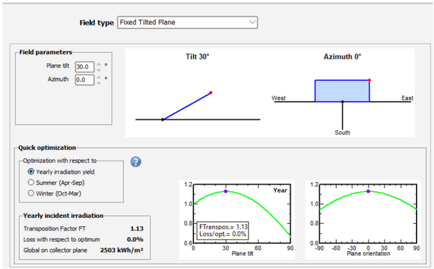

***Figure A:** Orientation of solar panels / **Şekil A:** Güneş panellerinin yönlendirilmesi*

Highlights (Önemli noktalar)

- *Determination of optimum tilt angle for increasing solar energy efficiency and detailed analysis of solar radiation/Güneş enerjisinin verimliliğini artırmak için optimum eğim açısının belirlenmesi ve güneş radyasyonunun detaylı analizi,*
- *Economic returns, investment return periods and financial analysis findings of 5 mwp and 10 mwp capacity solar power plants/5 MWp ve 10 MWp kapasiteli güneş enerji santrallerinin ekonomik getirileri, yatırım geri dönüş süreleri ve finansal analiz bulguları*
- *The role and impact of solar power plants in reducing dependence on fossil fuels and ensuring environmental sustainability/Fosil yakıtlara olan bağımlılığın azaltılmasında ve çevresel sürdürülebilirliğin sağlanmasında güneş enerji santrallerinin rolü ve etkisi,*

Aim (Amaç): *The objective of this study is to design, analyze the economic feasibility and evaluate the environmental sustainability benefits of 5 MWp and 10 MWp solar power plants in Ma'an, Jordan./Bu çalışmanın amacı, Ürdün Ma'an'da 5 MWp ve 10 MWp kapasiteli güneş enerji santrallerinin tasarımını gerçekleştirmek, ekonomik fizibilite analizleri yapmak ve çevresel sürdürülebilirlik faydalarını değerlendirmektir.*

Originality (Özgünlük): *The study presents an original analysis of solar power plant design and simulation in a semi-arid region such as Ma'an in Jordan. Technical details, economic feasibility and environmental benefits are comprehensively covered. / Çalışma, Ürdün'deki Ma'an gibi yarı kurak bir bölgede güneş enerjisi santrali tasarımı ve simülasyonu üzerine özgün bir analiz sunmaktadır. Teknik detaylar, ekonomik fizibilite ve çevresel faydalar kapsamlı bir şekilde ele alınmıştır.*

Results (Bulgular): *Simulation results show that 5 MWp and 10 MWp solar power plants can generate 10,691,025 kWh and 21,460,852 kWh of annual energy, respectively. Both plants have achieved high efficiency and environmental benefits. / Simülasyon sonuçları, 5 MWp ve 10 MWp kapasiteli güneş enerjisi santrallerinin sırasıyla 10,691,025 kWh ve 21,460,852 kWh yıllık enerji üretebileceğini göstermektedir. Her iki tesis de yüksek verimlilik ve çevresel fayda sağlamıştır.*

Conclusion (Sonuç): *This study highlights the importance of renewable energy investments in semi-arid regions by detailing the environmental and economic benefits in the design and simulation of solar power plants in Ma'an. / Bu çalışma, Ma'an'da güneş enerjisi santrallerinin tasarım ve simülasyonunda çevresel ve ekonomik faydaları detaylı olarak ortaya koyarak yarı kurak bölgelerde yenilenebilir enerji yatırımlarının önemini vurgulamaktadır.*

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Abstract

The energy sector in Jordan is facing major challenges due to the increasing demand for electricity and limited oil resources, which calls for the search for sustainable solutions. This study aims to present a comprehensive design of a solar power plant, starting with site selection in Ma'an, Jordan, where a careful analysis of solar radiation and environmental conditions was performed to ensure efficient production. The optimal tilt angle of the solar panels was determined at 30 degrees to maximize the absorption of solar radiation and improve system efficiency. In addition, a scientific methodology was applied to select the appropriate electrical cables, ensuring the minimization of electrical losses and achieving the highest operational efficiency. On the economic level, a comprehensive financial analysis was conducted to assess the investment feasibility of the project, where the results showed that the plant achieves high investment returns and a short payback period, which enhances the feasibility of investing in solar energy projects. Moreover, the amount of GHG emission reduction achieved by the plant was calculated, highlighting its effective role in reducing the carbon footprint and promoting environmental sustainability. This study reflects the importance of investing in solar energy projects, especially in semi-arid regions with high solar radiation, as they provide effective solutions to achieve energy sustainability and reduce dependence on fossil fuels.

Ma'an'da 5 MWp ve 10 MWp Güneş Enerjisi Santrallerinin Tasarımı ve Kapsamlı Simülasyonu: Ayrıntılı Sistem Tasarımı, Ekonomik Getiriler ve Yarı Kurak İklimde Çevresel Faydalar

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Öz

Ürdün'deki enerji sektörü, artan elektrik talebi ve sınırlı petrol kaynakları nedeniyle büyük zorluklarla karşı karşıyadır ve bu da sürdürülebilir çözümler aranmasını gerektirmektedir. Bu çalışma, Ürdün'ün Ma'an kentinde yer seçimi ile başlayan ve verimli üretim sağlamak için güneş radyasyonu ve çevresel koşulların dikkatli bir analizinin yapıldığı kapsamlı bir güneş enerjisi santrali tasarımı sunmayı amaçlamaktadır. Güneş panellerinin optimum eğim açısı, güneş radyasyonunun emilimini en üst düzeye çıkarmak ve sistem verimliliğini artırmak için 30 derece olarak belirlenmiştir. Buna ek olarak, uygun elektrik kablolarını seçmek için bilimsel bir metodoloji uygulanarak elektrik kayıplarının en aza indirilmesi ve en yüksek düzeyde operasyonel verimliliğin elde edilmesi sağlanmıştır. Ekonomik düzeyde, projenin yatırım fizibilitesini değerlendirmek için kapsamlı bir finansal analiz yapılmış ve sonuçlar tesisin yüksek yatırım getirisi ve kısa bir geri ödeme süresi elde ettiğini göstererek güneş enerjisi projelerine yatırım yapmanın fizibilitesini artırmıştır. Ayrıca, karbon ayak izinin azaltılması ve çevresel sürdürülebilirliğin teşvik edilmesindeki etkin rolü vurgulanarak, tesis tarafından elde edilen sera gazı emisyonu azaltım miktarı hesaplanmıştır. Bu çalışma, enerji sürdürülebilirliğini sağlamak ve fosil yakıtlara olan bağımlılığı azaltmak için etkili çözümler sağladığından, özellikle yüksek güneşlenme oranına sahip yarı kurak bölgelerde güneş enerjisi projelerine yatırım yapmanın önemini yansıtmaktadır.

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1. INTRODUCTION (GİRİŞ)

The combustion of fossil fuels significantly contributes to the accumulation of greenhouse gases in the atmosphere. This phenomenon accelerates anthropogenic climate change, causing adverse effects on terrestrial ecosystems and biodiversity [1]. The persistent increase in global energy demand, averaging an annual growth rate of approximately 1.8% since 2011, further intensifies these environmental challenges. This trend has directly amplified CO_2 emissions, exacerbating the global ecological footprint and intensifying pressure on planetary boundaries [2].

Recent assessments estimate that fossil fuel-related emissions and their associated health risks result in approximately 10.2 million premature deaths annually on a global scale. China accounts for the largest proportion of these fatalities (3.9 million), followed by India (2.5 million), with significant impacts also observed in Eastern Europe, the United States, and Southeast Asia. Nevertheless, mitigation measures, including a transition towards decarbonization and cleaner energy technologies, have reduced this figure to 8.7 million deaths annually, including a notable decrease of 1.5 million in China [3]. Recognizing the urgency of these challenges, the Rio Declaration in 1992 emphasized the necessity of finding alternatives to fossil fuels and reducing global reliance on them [4].

In the face of these challenges, solar energy has emerged as one of the most feasible solutions due to its low costs and limited environmental impact. Solar energy is characterized by its wide availability, with the Earth receiving far more solar energy than the annual global energy demand. Technological advances have reduced the operational costs of solar energy systems, boosting their widespread adoption [5]. Solar energy is one of the most promising renewable energy sources with its unlimited availability. The Earth receives solar energy at an intensity ranging from 0 to 1100 W/m², which is more than 16,000 times the global annual commercial energy demand and 61,000 times the total energy generated globally [6].

Like many countries, Jordan faces significant challenges in ensuring a reliable and sustainable energy supply. The primary factors include limited domestic fossil fuel resources and financial constraints in the energy sector [7]. Rapid urbanization, population growth, and geopolitical instability, including regional conflicts and refugee influxes, have also compounded electricity demand. These dynamics have heightened Jordan's dependence on energy imports, exposing the economy to volatility in global hydrocarbon markets and fiscal imbalances [8]. In response to these challenges, Jordan has prioritized the development of renewable energy sources, with solar energy emerging as a key solution. Solar energy systems not only address the growing electricity demand but also contribute to mitigating the environmental risks associated with fossil fuel use. By 2018, renewable energy accounted for 8% of Jordan's electricity generation, rising to 20% in 2020. This transition reduced reliance on natural gas and coal, which accounted for 33% and 43% of electricity generation in 2020. Jordan aims to increase the share of renewable energy further to 31% by 2030 while reducing the dependence on fossil fuels to 49% collectively [9]. Figure 1 shows the 2018 Electricity Generation Sources in Jordan and the Expected Electricity Sources in Jordan by 2030 [10].

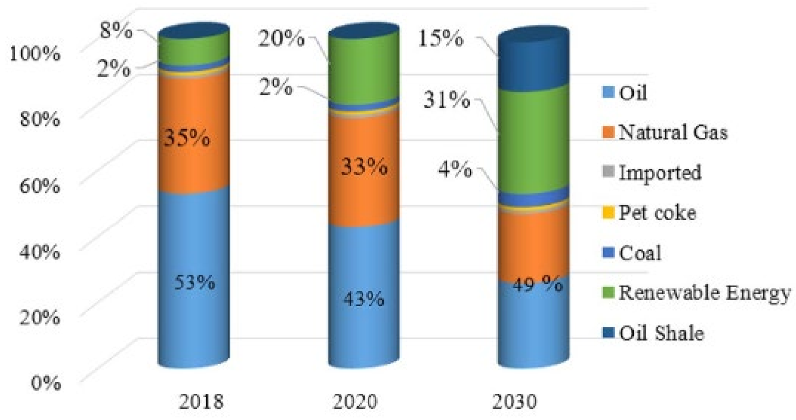

Figure 1. Distribution of current and future resources for electricity generation in Jordan (2018-2030) [10] (Ürdün'de elektrik üretimi için mevcut ve gelecekteki kaynakların dağılımı) (2018-2030)

Jordan is a country in the Middle East, located between 29° and 33° north latitude and 34° and 39° east longitude [11]. The desert constitutes about 72,660 km², equivalent to 80% of Jordan's total area. Desertification is a perennial challenge in the region, contributing to the depletion of natural resources and increasing migration rates. The desert is recognized for its harsh climate and high temperatures, scarce vegetation, and low population density [12].

This study encompasses the design and simulation of two solar power plants with a capacity of 5 MWp and 10 MWp, respectively, in Ma'an, Jordan. The selection of the site was initiated with an analysis of solar radiation and environmental conditions. Ma'an was selected due to its high solar radiation rates and clear skies for approximately 300 days per year [13]. The study's scope encompassed the calculation of the tilt angle and the number of solar panels, the determination of the appropriate cable diameter, and the selection of the most suitable inverter for the project. Additionally, the study evaluated the reduction in greenhouse gas emissions and the economic benefits of the solar power plant. The primary objective of the research is to provide a comprehensive analysis to enhance understanding of solar power plant design.

2. MATERIALS AND METHODS (MATERYAL VE METOD)

This section presents the methods and materials used in this study to achieve an accurate simulation of solar power plants. These methods include site selection, equipment selection, simulation and analysis methods, and calculation of economic return and greenhouse emissions.

2.1. Study Area Description (Çalışma Alanı Tanımı)

The southern regions of Jordan stand out as an ideal location for building solar power plants due to their vast areas, as shown in Figure 2 [14], where Ma'an records the highest values of solar radiation compared to the rest of the Jordanian governorates. The average daily radiation value ranges from 6670 to 6780 W/m². Table 1 shows the amount of solar radiation for each month [13].

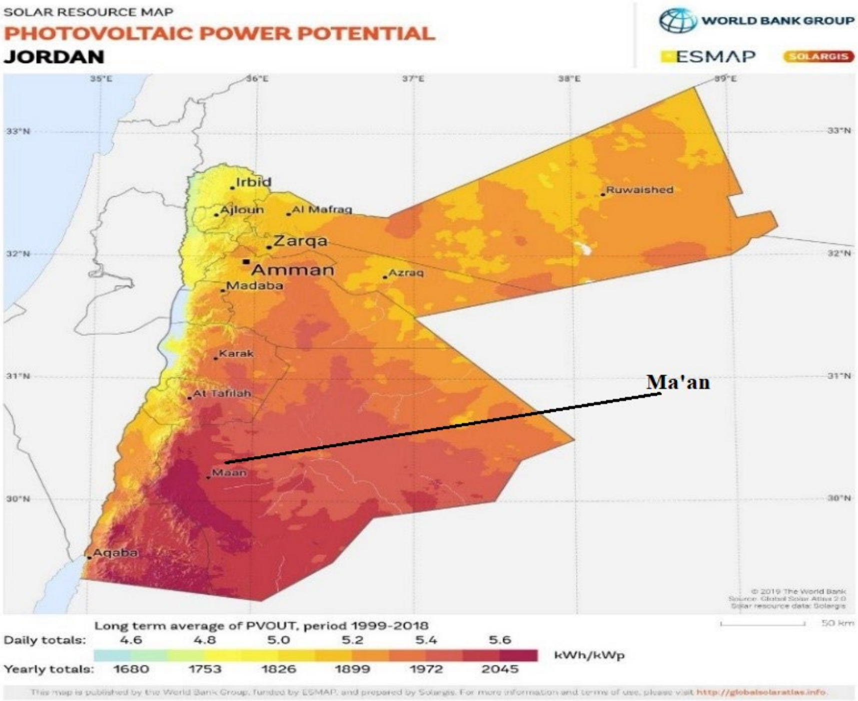

Figure 2. Photovoltaic electricity potential [14] (Fotovoltaik elektrik potansiyeli)

Table 1. Amount of solar radiation per month in Ma'an City (kWh/m²/Day)
(Ma'an Şehrinde aylık güneş radyasyonu miktarı) (kWh/m²/Gün)

Months	Solar Radiation (Ma'an)
January	5400
February	6280
March	7530
April	7150

May	7210
June	7470
July	7410
August	7500
September	7320
October	6930
November	5850

The location where the solar power plants are simulated is shown in Figure 3. This site is located in the city of Ma'an/Jordan at the coordinates of 30°14'49"N latitude and 35°41'37" E longitude.

Figure 3. The area where the solar power plants were simulated (Güneş enerjisi santrallerinin simüle edildiği alan)

2.2. Equipment and Tools Used (Kullanılan Ekipman ve Araçlar)

2.2.1. The inverter (İnvertör)

The inverter is the core component of the system, as it is responsible for converting the energy generated by the solar panels from direct (DC) to (AC). Therefore, choosing the right inverter is critical to ensure optimal system performance. For example, choosing an oversized centralized inverter can increase cabling costs. Longer cables, in turn, contribute to voltage drop, which should not exceed the maximum allowable 3% [15]. In addition, an oversized inverter may increase the self-consumption of energy, thus reducing the overall efficiency of the solar system.

On the other hand, choosing a small-sized inverter may restrict the electrical capacity, a phenomenon referred to as "power chopping." Power chopping occurs when the generated power exceeds the capacity of the inverter, leading to overheating of the inverter and the possibility of malfunctions or significant power losses [16,17].

This study selected the 111.1 kW inverter after a thorough analysis to ensure optimal system efficiency and minimize power losses. The total power of the inverters was determined to meet the system's requirements, and the voltage and current values were selected to be compatible with the solar panels. The simulation results determined that the 111.1 kW inverters operate with minimum losses in the system and provide high efficiency. Furthermore, the economic viability of the inverters and their alignment with the project's technical specifications were taken into account. Table 2 provides the detailed specifications of the inverter used. The following equation was used to determine the required number of inverters for 5 MWp and 10 MWp solar systems.

$$\text{Number of Inverterts}=\frac{\text{AcPower}}{\text{InverterPower}} \quad (1)$$

Table 2. Inverter datasheet (İnvertör veri sayfası)

Max. Efficiency	98.6%
Input	
Max. Input Voltage	1100 V
Max. Current per MPPT	26 A
Max. Short Circuit Current per MPPT	40 A
Start Voltage	200 V
MPPT Operating Voltage Range	200 V ~ 1000 V
Rated input voltage	650 V (420 V/440 V), 720 V (480 V)
Maximum number of input channels	20
Number of MPP Trackers	10
Output	
Rated Output Power	111,100 W
Max. AC Apparent Power	125,000 VA
Max. AC Active Power (cosφ=1)	111,100 W
Rated Output Voltage	242 V/420 V,254 V/440 V and 277 V/480 V, 3W+PE
Rated AC Grid Frequency	50 Hz/60 Hz
Output Voltage Frequency	152.8 A (420 V), 145.8 A (440 V), 133.7 A (480 V)
Max. Output Current	171.9 A (420 V), 164.1 A (440 V), 150.4 A (480 V)
Adjustable Power Factor Range	0.8 LG ... 0.8 LD
Max. Total Harmonic Distortion	< 3%

2.2.2. The solar panel (Güneş paneli)

Solar panels are the primary components responsible for generating electricity by converting light radiation into electrical energy, a process known as the photovoltaic effect. When selecting solar panels for a particular project, it is recommended that certifications such as IEC be obtained. These certifications are essential because they include evaluative tests for performance, safety, energy efficiency under different environmental conditions, corrosion resistance, the extent of potential induced degradation (PID), and manufacturing quality [18]. When solar panels are connected in series, the system voltage increases, while the current increases when they are connected in parallel [17]. Therefore, it is necessary to determine the optimal number of panels and their proper connection configuration, either in series or parallel, to avoid risks that may lead to system failure or fires due to mismatched system inputs and inverter specifications. Detailed specifications of the solar panels used in this project are given in Table 3.

Table 3. Solar panel datasheet (Güneş paneli veri sayfası)

Module Type	**Tiger Neo N-type 72HL4-(V) 570-590 Watt**
Maximum Power (Pmax)	590 Wp
Maximum Power Voltage (Vmp)	43.71V
Maximum Power Current (Imp)	13.50A
Open-circuit Voltage (Voc)	52.63V
Short-circuit Current (Isc)	14.13A
Module Efficiency STC (%)	22.84%
Operating Temperature (C°)	40 C° ~+85 C°
Maximum system voltage	1000/1500VDC (IEC)
Maximum series fuse rating	25A
Power Tolerance	0~+3%
Temperature coefficients of Pmax	-0.29% / C°
Temperature coefficients of Voc	-0.25% / C°
Temperature coefficients of Isc	0.045% / C°
Nominal operating cell temperature (NOCT)	45-+2 C°

To ensure that the inverter works efficiently, the voltage of the solar panels connected in series must not exceed the maximum allowable inverter voltage, which is 1000V. The inverter also requires a voltage of at least 200V to function properly, according to Table 2 in the inverter datasheet.

Equation (2) is used to calculate the maximum number of solar panels that can be connected in series.

$$V_{(Max)} = V_{oc,stc} \times \left[1 + TempCoff. \times (\Delta T)\right] \quad (2)$$

where, $V_{oc,stc}$ is the open circuit voltage of the solar panel, and *TempCoff* is the temperature coefficient of voltage, representing the rate of change of voltage relative to temperature change (measured in %/°C). The difference between the minimum temperature recorded at the site and the standard test condition temperature (Tstc=25°C) is also considered. These parameters are used to determine the maximum number of panels that can be connected in series.

Equation (3) is used to calculate the minimum number of solar panels to be connected in series.

$$V_{(Min)} = V_{mpp,stc} \times \left[1 + TempCoff. \times (\Delta T)\right] \quad (3)$$

where $V_{mpp,stc}$ is the solar panel's maximum power point voltage.

2.2.3. Sizing DC cable (DC kablosunun boyutlandırılması)

The selection of conductors in solar power systems is a critical factor in ensuring operational efficiency and electrical safety. The performance of conductors depends on multiple parameters, including the type of conductive material, cross-sectional area, insulation properties, and ampacity. An improper selection may lead to voltage drop, overheating, and, in extreme cases, fire hazards [19,20]. Therefore, various considerations must be accounted for, such as the expected current load, voltage rating, environmental conditions, and the installation method whether routed through conduits or exposed to open-air conditions. The following equation is used to calculate the cross-section of a cable.

$$A = 1.25 \times \frac{2 \times L \times I \times \rho}{V_{Drop}} \quad (4)$$

The cable cross-sectional area *(A)* is determined by considering several factors, where *L* is the one-way length of the cable in meters, *I* is the electrical current (typically based on the short-circuit current, Isc, to ensure a sufficient safety factor), and *ρ* is the electrical resistivity, which is 0.0171 Ω·m for copper and 0.0274 Ω·m for aluminum. Additionally, a maximum acceptable voltage drop (V_{Drop}) of 3% is considered to ensure efficient electrical system performance.

2.3. Simulation Procedure (Simülasyon Prosedürü)

In this study, a comprehensive simulation of two solar power plants (5 MWp and 10 MWp) was performed to evaluate their performance and estimate the amount of energy that can be produced under the climatic conditions in the city of Ma'an at coordinates 30°14'49" North and longitude 35°41'37" East. The simulation aims to provide an overview of the efficiency of the system at a specific location, where solar energy production depends on several factors, such as daily solar radiation, temperature, and the angle of inclination of the solar panels.

This simulation is based on a set of climatic inputs obtained from the Meteonorm 8.1 database (temperature, wind speed, direct and reflected solar radiation), as well as using the solar panel datasheet in Table 3 and the inverter's datasheet in Table 2. The PVsyst software was used to simulate the plant's performance throughout the year, and the program provides an estimate of monthly and annual power outputs based on the solar radiation information obtained from Meteonorm 8.1 and analyzes the losses in the entire system.

2.3.1. The solar panel orientation (Güneş paneli yönlendirmesi)

Tilt angle is one of the most important factors to consider when designing solar energy systems because it affects the amount of solar radiation collected by the panels. The optimal tilt angle is determined by geographic location. Every geographical area has an ideal tilt angle [21,22]. Photovoltaic (PV) modules are oriented to the south using the azimuth angle. An azimuth angle of -90° points east, 0° points south, and +90° points west. For optimal sun exposure, orient the azimuth angle south in the northern hemisphere and north in the southern hemisphere [21]. The azimuth angle is the angle between the solar panel's horizontal plane and the sun's direction.

Solar Declination angle One of the main factors affecting the Sun's motion is the declination angle, the angle between the Sun's position and the straight line of the sky. This angle varies between +23.5 degrees and -23.5 degrees throughout the year and is equal to zero at the equinoxes when day and night are equal. The spring equinox usually occurs around March 20, and the fall equinox usually occurs around September 22 [23]. The sun's declination angle is calculated using the following equation.

$$\delta = 23.45 \times \mathrm{Sin}\left[\frac{360}{365} \times \left(N_{day} - 81\right)\right] \quad (5)$$

where N_{day} represents the Nth day of the year.

Elevation angle in solar panel systems, the elevation angle refers to the tilt or inclination of the panels relative to the horizontal plane. This angle is crucial for optimizing solar energy capture efficiency. Adjusting the elevation angle of the solar panels allows them to receive maximum sunlight throughout the day, thus maximizing energy production [24]. The ideal elevation angle varies depending on factors such as geographical location, time of year, and specific energy needs. Correct elevation angle adjustment can significantly improve the performance and efficiency of solar panel installations. The elevation angle is calculated using the following equation.

$$\beta = 90^{\circ} - L + \delta \quad (6)$$

where L represents the latitude of the location.

The tilt angle is the angle between the solar panels and the Earth's surface. This angle indicates that the solar panels are oriented towards direct solar radiation. The tilt angle is calculated using the following equation.

$$\alpha = 90^{\circ} - \beta \quad (7)$$

When applying the equations to calculate the tilt angle, the optimal angle was determined for each month, as shown in Table 4. However, since the ground-mounted solar system operates year-round without a tracking mechanism, it is essential to identify the optimal fixed tilt angle that maximizes solar radiation absorption across all seasons. After implementing the calculated tilt angles into the PVsyst simulation software, the optimal tilt angle that delivers the highest energy yield and overall system performance was found to be 30 degrees.

Table 4. Solar declination, elevation angle, and inclination angle values for each month
(Her ay için güneş sapması, yükseklik açısı ve eğim açısı değerleri)

Month	N^{th} day of the year	Sun Declination Angle (δ)	Elevation Angle (β)	Tilt Angle (α)
January	1	-23.01	36.7428	53.26
February	32	-17.51	42.2428	47.76
Mart	60	-8.29	51.4628	38.53
April	91	4.0	63.7528	26.25
May	121	14.9	74.6528	15.35
June	152	22.03	81.7828	8.22
July	182	23.1	82.8528	7.15
August	213	17.9	77.6528	12.35
September	244	7.72	67.4728	22.53
October	274	-4.21	55.5428	34.46
November	305	-15.36	44.3928	45.61
December	335	-22.1	37.6528	52.35

The optimal tilt angle for solar panels is chosen based on several factors that affect the solar panel's ability to receive solar radiation and convert it into electrical energy. Among these factors, the first is the transmission factor (FT), which measures the amount of solar radiation received on an inclined surface compared to the radiation on a horizontal surface. The higher the FT value, the better the angle is for receiving the largest amount of solar radiation [25]. The highest FT value recorded in the data is 1.13 at an inclination angle of 30°, indicating that this angle allows the solar panels to receive the largest amount of solar radiation, thus obtaining the highest energy conversion efficiency. In addition, when analyzing the losses relative to the ideal, we find that the 30° tilt angle achieves losses of 0.0%, which means it is the optimal angle to minimize energy losses. This enhances the effectiveness of solar panels in generating power with minimal losses. This enhances the effectiveness of solar panels in generating power with minimal losses.

Additionally, the total solar radiation on the solar panel surface peaks at a 30° inclination, amounting to 2503 kWh/m². This indicates that solar panels installed at a 30° tilt angle will collect the most solar energy throughout the year compared to other tilt angles. Figure 4 shows the tilt angle in PVsyst, the azimuth angle, the transposition factor, and the global irradiance at the collector plane (kWh/m^2).

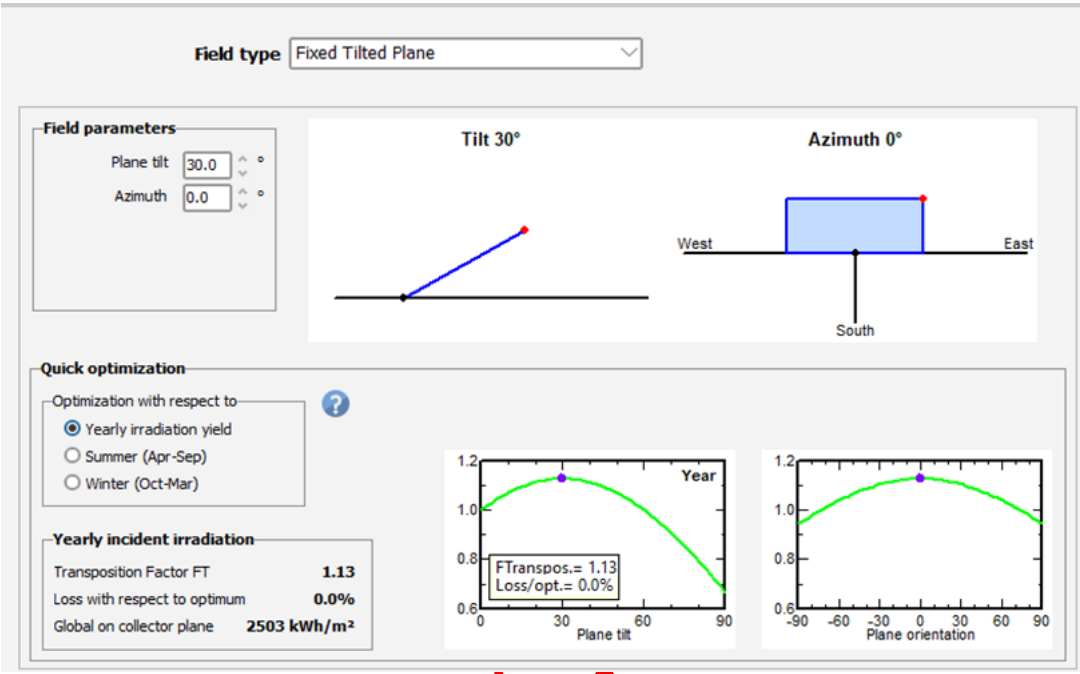

Figure 4. Orientation of solar panels (Güneş panellerinin yönlendirilmesi)

2.3.2. Distance between solar panel rows (Güneş paneli sıraları arasındaki mesafe)

The distance between rows of solar panels is important to avoid shading and optimize energy capture efficiency. The ideal distance is determined based on the angle of inclination of the panels and the number of panels installed on each structure. Recently, photovoltaic (PV) module use has seen a significant increase in installations of various types, both large and small. However, the performance of PV panels is significantly affected by shading effects caused by peripheral factors such as shadows from trees, passing clouds, or neighboring buildings. To achieve optimal performance, avoid shading conditions to the greatest extent possible [26,27].

The shadow length is calculated using the following equation, and Figure 5 shows all the details.

$$H = \mathrm{Sin}(\alpha) \times 7.233 \tag{8}$$

where H is the height of the solar panel, and α is the tilt angle of the panel.

$$D = \frac{H}{\tan(\alpha)} \tag{9}$$

where D is the shadow length, H is the height of the solar panel, and α is the tilt angle of the panel.

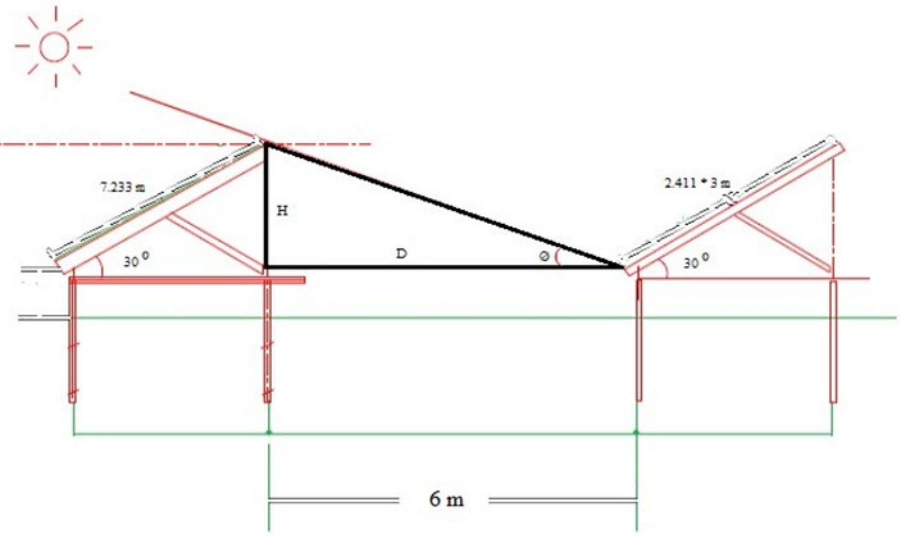

Figure 5. The details of shadow length (Gölge uzunluğunun detayları)

2.3.3. Solar panel system simulation parameters
(Güneş paneli sistemi simülasyon parametreleri)

The necessary solar power system parameters are entered, such as solar panel type, number and type of inverters, panel connection (series and parallel connection), and solar power system capacity. Figure 6 shows a 5 MWp solar power system consisting of about 8475 JinkoSolar solar panels, where 15 modules are connected in series in 565 modules in strings that were used in this system. Connecting the panels in parallel was not used because string inverters were used in the simulation, where the maximum current value of each MPPT is 26 A, while each solar panel produces 13.5 A. If the panels are connected in parallel, the current will exceed the inverter's maximum limit, which could lead to inverter failure or technical malfunctions.

The nominal capacity of the solar power plant is 5000 kWp. To convert power from DC to AC, 45 Huawei inverters with 111.1 kW per inverter were used for a total inverter capacity of 5000 kW. The operating limits of the inverters are from 200 to 1000 volts.

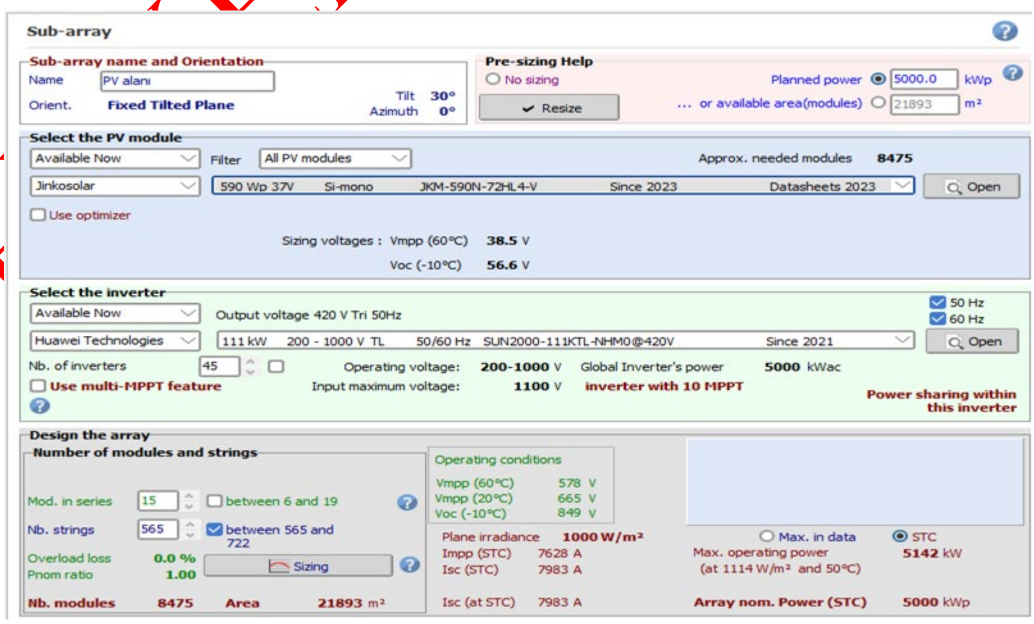

Figure 6. The interface where parameters are entered for a 5 MWp capacity power plant using the PVsyst program (PVsyst programı kullanılarak 5 MWp kapasiteli bir enerji santrali için parametrelerin girildiği arayüz)

Figure 7 shows a 10 MWp solar power system consisting of about 16949 JinkoSolar solar panels, where 17 modules are connected in series in 997 modules in strings that were used in this system. No parallel connections were used in this simulation.

The nominal capacity of the solar power plant is 10000 kWp. To convert power from DC to AC, 90 Huawei inverters with 111.1 kW per inverter were used for a total inverter capacity of 10000 kW. The operating limits of the inverters are from 200 to 1000 volts.

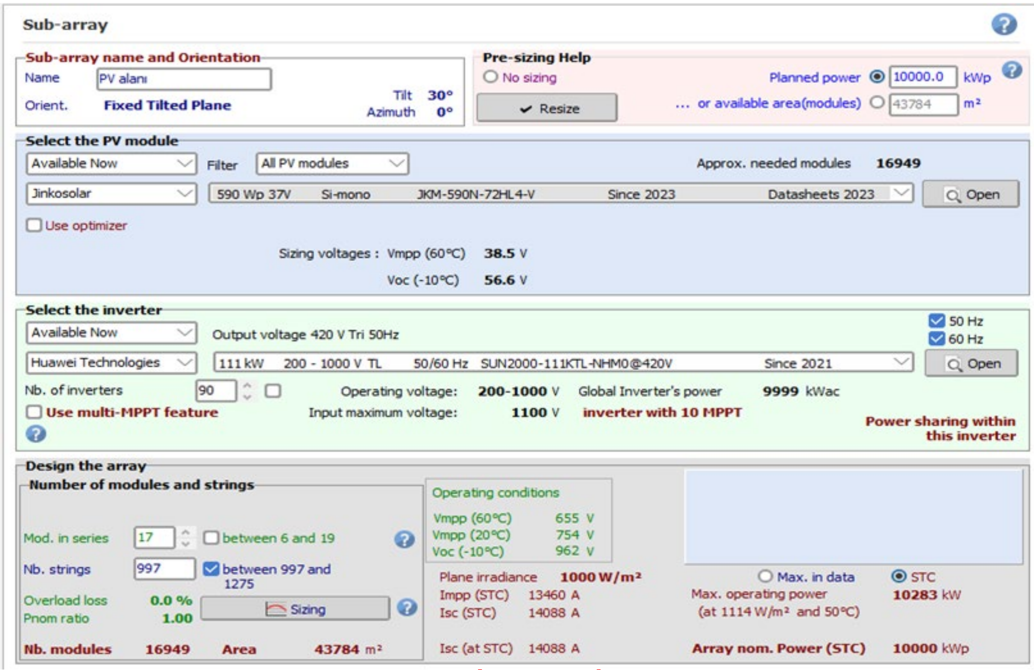

Figure 7. The interface where parameters are entered for a 10 MWp capacity power plant using the PVsyst program (PVsyst programı kullanılarak 10 MWp kapasiteli bir enerji santrali için parametrelerin girildiği arayüz)

2.3.4. Solar power plant construction cost (Güneş enerjisi santrali yapım maliyeti)

The economic feasibility of any solar energy project depends on key factors, the first of which is the cost of establishing solar power plants, as the cost of establishing a solar power plant varies depending on several factors, including geographical location, the size of the solar plant, the type of solar panels used, installation and infrastructure costs. The financial return of a solar power plant depends on the productivity of the solar power plant versus the initial construction cost. If the cost is high and efficient equipment is not selected, it is likely that the return will not be as good or may take longer to recover the capital.

Therefore, analyzing the construction costs and selecting the right equipment maximizes the financial return and reduces the payback period, boosting investment in solar projects.

In this section, the costs and economic returns of the 5 MWp and 10 MWp solar power plants in Ma'an will be explained, and the payback period will be calculated. Table 5 shows the initial investment costs, operating and maintenance expenses, energy production capacities, and revenues for both plants.

Indirect costs (5-10%) are Permit, Engineering project, Financial modeling, Geodetic services, Site supervision, access to engineering, communication, Site safety, and construction insurance.

Table 5. Installation costs for 5 MWp and 10 MWp solar power plants (5 MWp ve 10 MWp güneş enerjisi santralleri için kurulum maliyetleri)

Direct costs	5 MWp power plant equipment cost (US $)	10 MWp solar power plant equipment cost (US $)
Pv modules	1,555,045	3,109,908
Inverters	600,000	1,200,000

Metal load-bearing structures	900,000	1,800,000
DC and AC cables	360,000	600,000
Electrical protective equipment	120,000	120,000
Transforming station	1,000,000	2,400,000
High/medium voltage lines	420,000	600,000
Fences, cameras, and security measures	250,000	360,000
Other engineering elements, such as improved lighting and access roads, depending on the investor's requirements	300,000	600,000
Indirect costs	450,000	900,000
Land cost (if applicable)	No	No
Total	5,955,045	11,689,908

2.3.5. The economic analysis of solar power plants (Güneş enerjisi santrallerinin ekonomik analizi)

A feasibility study must be conducted to assess the effectiveness of the solar power plant in terms of production, economic return, and payback period, and the Net Present Value (NPV), Internal Rate of Return (IRR), and Profitability Index (PI) values must be calculated [28].

- NPV: Equation 10 is used to calculate NPV, which refers to assessing the profitability of an investment by calculating the difference between the present value of all cash inflows and outflows over the project's 30-year life. The NPV formula takes into account annual cash flows and the interest rate. If the value is greater than zero, the project is considered profitable. When calculating NPV using Equation 10, the initial investment cost (C_o), the annual revenue generated by the solar plant (C_t), the discount rate or required rate of return (expected profit for the investor) (r), and the life span of the project (T) are used.

$$NPV = -C_o + \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} \qquad (10)$$

- IRR: IRR is calculated using equation 11 and refers to the discount rate that makes the NPV equal to zero. The IRR value is used to assess whether an investment is worthwhile or not. The higher the IRR value, the better the financial return. The IRR should be compared to the country's interest rate to determine the feasibility of the investment, as the interest rate in Jordan was 12%.

$$0 = NPV = \sum_{t=1}^{T} \frac{C_t}{(1+IRR)^t} - C_o \qquad (11)$$

- IRR, the profitability index, is calculated using Equation 12 and measures the amount of profit or loss the project realizes compared to the initial investment. The PI value is calculated by dividing the net present value by the initial investment. If the profitability index is greater than 1, the project is considered profitable. The profitability index is used to evaluate projects holistically, where the NPV, P&L, and IRR are used together as a single metric.

$$PI = \frac{\boldsymbol{NPV}}{\textbf{Initial Investment Cost}} \qquad (12)$$

3. SOLAR POWER PLANTS SIMULATION RESULTS (GÜNEŞ ENERJISI SANTRALLERI SIMÜLASYON SONUÇLARI)

In this section, the monthly and annual production of 5 MWp and 10 MWp solar power plants will be presented and analyzed, and the amount of GHG reductions produced by each plant will be evaluated with a detailed analysis of the economic return of each plant. Finally, a comparison will be made between the two plants to determine the best performance based on the criteria studied.

3.1. Simulation Results (Simulasyon Sonuçları)

The ambient temperature varies between 7.35 °C and 13.87 °C in winter and between 17.83 °C and 27.53 °C in summer. The average solar radiation was 110.1 kWh/m² in December and 260.5 kWh/m² in June. The lowest and highest measured temperatures were 7.35 °C in January and 27.56 °C in July, respectively.

Table 6 shows the simulation results of a 5 MWp solar power plant obtained using the PVsyst program. The table includes important parameters such as annual energy production and environmental impacts. Among these data, the highest solar radiation value was measured in June (260.5 kWh/m²), while the lowest value was recorded in December (110.1 kWh/m²). The total annual energy production E-Array value of the solar panel was 10,924,989 kWh. The lowest efficiency rate (82.8%) was recorded in August, while the highest efficiency rate (91.1%) was recorded in January.

Table 6. Simulation results for a 5 MWp solar power plant (5 MWp güneş enerjisi santrali için simülasyon sonuçları)

	GlobHor (kWh/m²)	DiffHor (kWh/m²)	Tamb (°C)	GlobInc (kWh/m²)	GlobEff (kWh/m²)	E-Array (kWh)	E-Grid (kWh)	PR rate
January	114.5	30.26	7.35	174.1	171.7	809426	793177	0.911
February	127.0	34.34	9.58	169.7	167.3	778078	761950	0.898
March	181.5	46.12	14.20	214.2	210.6	959743	939079	0.877
April	211.0	57.56	17.83	219.6	215.3	968489	947484	0.863
May	242.5	56.16	22.58	223.7	218.5	970926	949886	0.849
June	260.5	37.75	25.44	226.5	220.7	967095	945896	0.835
July	255.7	45.22	27.56	228.2	222.2	967965	946755	0.830
August	233.2	49.55	27.55	230.7	225.5	976958	955496	0.828
September	197.2	42.74	24.79	221.8	217.5	948512	927662	0.836
October	162.9	37.97	20.68	211.0	207.7	925736	905754	0.858
November	126.0	28.97	13.87	185.8	183.5	842035	824166	0.887
December	110.1	26.76	8.95	174.8	172.6	810028	793722	0.908
Yearly	2222.3	493.40	18.41	2480.2	2432.9	10,924,989	10,691,025	0.862

Table 7 shows the results of simulating the performance of a 10 MWp solar power plant using the PVsyst program. The simulation shows that the annual power output of the plant is 21,848,173 kWh E-Array, while the amount of electricity supplied to the national grid is 21,460,852 kWh E-Grid. The plant's efficiency is lowest in August at 83.1% and highest in January at 91.4%. This decrease in efficiency during the summer months is due to higher temperatures, as solar panels operate more efficiently in cold weather conditions during the winter [29].

Table 7. Simulation results for a 10 MWp solar power plant (10 MWp güneş enerjisi santrali için simülasyon sonuçları)

	GlobHor (kWh/m²)	DiffHor (kWh/m²)	Tamb (°C)	GlobInc (kWh/m²)	GlobEff (kWh/m²)	E-Array (kWh)	E-Grid (kWh)	PR rate
January	114.5	30.26	7.35	174.1	171.7	1618752	1591747	0.914
February	127.0	34.34	9.58	169.7	167.3	1555907	1529657	0.901
March	181.5	46.12	14.20	214.2	210.6	1919180	1885844	0.880
April	211.0	57.56	17.83	219.6	215.3	1936746	1902468	0.867
May	242.5	56.16	22.58	223.7	218.5	1941738	1907228	0.852
June	260.5	37.75	25.44	226.5	220.7	1934077	1898579	0.838
July	255.7	45.22	27.56	228.2	222.2	1935814	1899925	0.833
August	233.2	49.55	27.55	230.7	225.5	1953800	1916908	0.831
September	197.2	42.74	24.79	221.8	217.5	1896883	1861257	0.839
October	162.9	37.97	20.68	211.0	207.7	1851362	1818553	0.862
November	126.0	28.97	13.87	185.8	183.5	1683967	1655415	0.891
December	110.1	26.76	8.95	174.8	172.6	1619947	1593270	0.912
Yearly	2222.3	493.40	18.41	2480.2	2432.9	21,848,173	21,460,852	0.865

3.2. Results of the Amount of GHG Reductions Produced by Each Solar Power Plant (Her Bir Güneş Enerjisi Santrali Tarafından Üretilen Sera Gazı Azaltım Miktarının Sonuçları)

The performance of two solar power plants was evaluated in terms of greenhouse gas (GHG) emission reductions. This section aims to present the overall results of the GHG reductions achieved by both solar power plants. The results show that the 10 MWp solar plant provides greater benefits, reducing CO_2 emissions by 333,418 tCO_2 compared to the 166,112 tCO_2 reduced by the 5 MWp plant.

3.2.1. Emission reduction potential of solar power plants compared to fossil fuels (Fosil yakıtlara kıyasla güneş enerjisi santrallerinin emisyon azaltma potansiyeli)

Today, energy production is of great importance due to its environmental impacts. Solar energy offers an alternative to fossil fuels as a renewable and environmentally friendly energy source. While fossil fuels (coal, natural gas, and oil) contribute to climate change with their high carbon dioxide (CO_2) emissions, solar energy can generate energy with almost zero emissions. In this section, solar energy will be compared with fossil fuels in terms of carbon emissions and its environmental impacts will be examined in detail.

To determine how much a solar power plant saves greenhouse gases compared to fossil fuels, the emission factor of each fuel type needs to be known. The emission factor of petroleum is 541 gCO_2/kWh [30], while the emission factor of natural gas is 473 gCO_2/kWh [31]. The following equation can be used to calculate the emission factor:

$$\text{Total Emission} = \frac{\text{Total energy produced}}{\text{Total } CO_2 \text{ Emissions}} \quad (13)$$

A 5 MWp solar power plant generates 10,691,025 kWh of energy per annum. From coal, the emission coefficient of petroleum (541 gCO_2/kWh) is applied to calculate the resulting CO_2 emissions, which amount to 5,783,844,525 gCO_2. This is equivalent to 5,783.84 tCO_2.Similarly, a 10 MWp solar power plant generates 21,460,876 kWh of energy annually. From coal, the emission coefficient of oil (541 gCO_2/kWh) is applied to calculate the resulting 11,610,333,961 gCO_2 emissions, which is equivalent to 11,610.33 tCO_2.

A 5 MWp solar power plant generates 10,691,025 kWh of energy annually. When considering emissions from natural gas, multiplying this production amount by 473 gCO_2/kWh -the emission coefficient of oil- results in 5,056,854,825 gCO_2 emissions. This value equates to 5,056.85 tCO_2.

Similarly, a 10 MWp solar power plant generates 21,460,876 kWh of energy annually. Accounting for emissions from natural gas, multiplying this production amount by 473 gCO_2/kWh -the emission coefficient of oil- yields 10,150,994,348 gCO_2 emissions. This value corresponds to 10,150.99 tCO_2.

A 5 MWp solar power plant has the potential to produce 5,783.84 tCO_2 emissions annually if it were to run on oil. The 10 MWp plant's emissions would be 11,610.33 tCO_2 per year. Similarly, if both plants operate on natural gas, the annual emissions of the 5 MWp plant are calculated as 5,056.85 tCO_2 and the emissions of the 10 MWp plant as 10,150.99 tCO_2. Although natural gas's emission factor is lower than oil, it still causes significant emissions compared to solar energy.

3.3. Feasibility and Financial Return Results (Fizibilite ve Finansal Getiri Sonuçları)

Revenues from the sale of energy produced by solar power plants are determined based on the unit price of the electricity generated, as shown in Table 8. The purchase price of a solar energy unit in Jordan is about 0.135 JD, approximately 0.19 USD [32]. Determining the price of electricity per kilowatt-hour is important in the financial analysis of solar energy projects, as it greatly helps assess the project's economic benefit. Table 8 presents a comparison between the annual electricity generation, selling price, annual return, and rate of return on investment for two solar projects of 5 and 10 MWp.

Table 8. 5 MWp and 10 MWp power plants' energy sales revenues 5 MWp ve 10 MWp kapsiteli santrallerin enerji satış gelirleri

Parameter	5 MWp plant	10 MWp plant
The initial production cost of the solar plant ($)	5,955,045	11,689,908
Total Production (kWh/year)	10,691,025	21,460,876
Sales Price ($/kWh)	0.19	0.19
Annual Return ($)	2,031,294.75	4,077,566.44

Return Rate (Year/Month)	2/11	2/10
PV system life (Year)	30	30
Solar panel degradation per year (%)	0.40	0.40

The NPV of the 5 MWp solar power plant was $9,885,201, indicating that the return from the project exceeds the initial investment cost and is, therefore, profitable in the long term. The internal rate of return was 33.60%, reflecting the project's annual internal rate of return, while the profitability rate was 2.66.

The NPV of a 10 MWp solar power plant is $20,107,376, with an internal rate of return of 34.37% and a profitability index of 2.7201. These values indicate that the profitability of a larger solar power plant is higher despite the higher initial cost. However, the economic return is better in the long term. Table 9 shows the economic analysis results.

Table 9. Economic analysis results (Ekonomik analiz sonuçları)

Parameter	**5 MWp PV plant**	**10 MWp PV plant**
NPV ($)	9,885,201	20,107,376
IRR (%/year)	0.336	0.3437
PI	2.66	2.72
Energy Production Capacity (kW)	10,691,025	21,460,876
greenhouse gases saved (tCO_2)	166,112	333,418
Payback Period (Year/Month)	2 / 11	2 / 10

The following Figures 7 and 8 show the economic return of solar power plants over 30 years. It shows that the first year has the highest yield, while the yield gradually decreases over time due to the degradation in solar panel efficiency by up to 0.40%. Figures 7 and 8 provide an important reference point for investors by providing a holistic view of the total economic return over the lifetime of the plant. Thus, the impact of the loss of solar panel efficiency over time on the long-term economic return can be clearly and accurately analyzed. The following equation can be used to calculate the percentage change in the annual economic return.

$$PC = \frac{AR - PYR}{PYR} \tag{14}$$

where *PC* is the Percentage Change, *AR* is Annual Revenue, income, or returns for the current year, and *PYR* is the income or returns for the previous year.

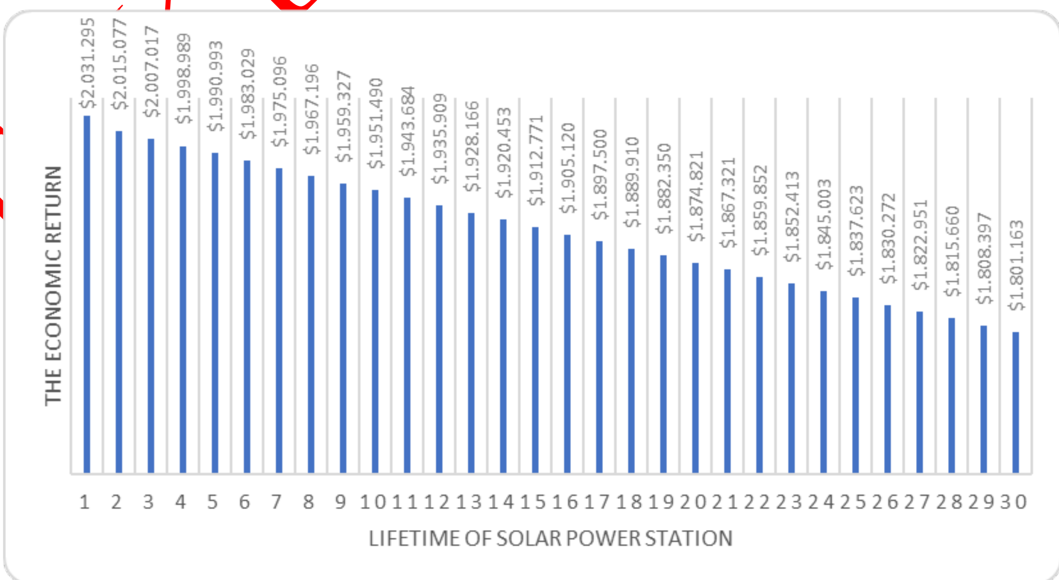

Figure 7. The economic return of a 5 MWp solar power plant in 30 years (5 MWp'lik bir güneş enerjisi santralinin 30 yıl içindeki ekonomik getirisi)

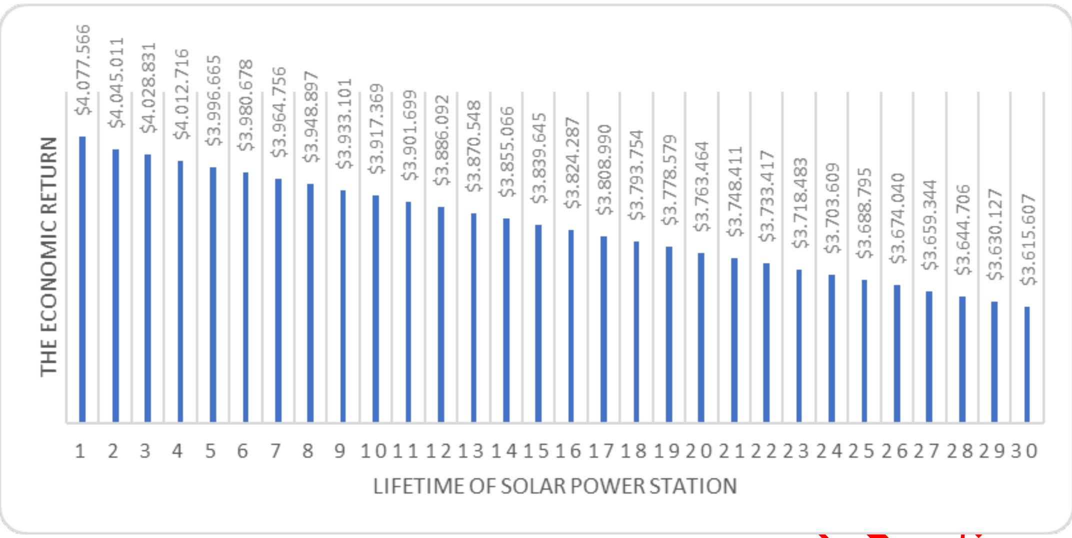

Figure 8. The economic return of a 10 MWp solar power plant in 30 years (5 MWp'lik bir güneş enerjisi santralinin 30 yıl içindeki ekonomik getirisi)

4. CONCLUSIONS (SONUÇLAR)

This study presents a comprehensive evaluation of the design, simulation, and financial feasibility of 5 MWp and 10 MWp solar power plants in Ma'an, Jordan. The analysis showed that the optimal tilt angle for capturing solar energy is 30°, which ensures efficient absorption of solar radiation. Proper cable selection was made to minimize electrical losses. The simulation results proved that the 5 MWp solar plant generates 10,924,989 kWh per year, while the 10 MWp plant produces 21,460,852 kWh per year. Thus, the larger plant provides higher energy production and greater environmental benefits, offsetting 333,418 tCO_2 emissions over its lifetime, compared to 166,112 tCO_2 for the 5 MWp plant. From an economic perspective, the net present value of the 5 MWp system was calculated at $9,885,201, while the 10 MWp plant achieved a higher net present value of $20,107,376, indicating a stronger financial capacity. In addition, the IRR was 33.6% for the 5 MWp plant and 34.37% for the 10 MWp plant, both of which exceed typical investment criteria. Payback periods were also very favorable, at 2 years and 11 months for the 5 MWp system and 2 years and 10 months for the 10 MWp system. The results highlight the economic and environmental advantages of large-scale solar investments in semi-arid regions. The results confirm that a 10 MWp solar power plant is the best option, offering higher financial returns and greater potential for CO_2 reduction. Future research should explore the integration of energy storage to further improve performance, improve grid stability, and ensure a more reliable and sustainable energy transition.

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This manuscript has been extracted from an MSc dissertation conducted at Kütahya Dumlupınar University. All data, models, and data codes generated or used during the study appear in the published article.

Bu makale Kütahya Dumlupınar Üniversitesi'nde tamamlanan yüksek lisans tezinden üretilmiştir. Çalışma sırasında üretilen veya kullanılan tüm veriler, modeller ve veri kodları yayınlanan makalede yer almaktadır.

DECLARATION OF ETHICAL STANDARDS (ETİK STANDARTLARIN BEYANI)

The author of this article declares that the materials and methods they use in their work do not require ethical committee approval and/or legal-specific permission.

Bu makalenin yazarları çalışmalarında kullandıkları materyal ve yöntemlerin etik kurul izni ve/veya yasal-özel bir izin gerektirmediğini beyan ederler.

AUTHORS' CONTRIBUTIONS (YAZARLARIN KATKILARI)

The authors contributed to this article as follows:

Ibrahim Mahmoud Rizeq ALSAQAR:

- Literature review: Conducting literature research to create the academic infrastructure of the study
- Simulation and Modeling: Performing simulations with PVsyst software and detailing the system design
- Article Writing: Writing the study according to the journal format

- Literatür taraması: Çalışmanın akademik altyapısının oluşturulması için literatür araştırmasının yapılması
- Simülasyon ve Modelleme: PVsyst yazılımıyla simülasyonların gerçekleştirilmesi ve sistem tasarımının detaylandırılması
- Makale Yazımı: Dergi formatına göre çalışmanın yazılı hale getirilmesi

Mehmet ERDEM:

- Idea and Design: Development of the idea and overall design of the study.
- Final Approval: Approval of the final version of the manuscript and preparation for publication
- Overall management of the process

- Fikir ve Tasarım: Çalışmanın fikrinin geliştirilmesi ve genel tasarımın oluşturulması.
- Son Onay: Makalenin nihai halinin onaylanması ve yayıma hazırlanması
- Sürecin genel yönetimi

Stages to which both authors contributed jointly:

- Environmental and Economic Impacts: Conducting and interpreting environmental and economic analysis
- Revision: Addressing the comments made by the editor and reviewers and making corrections.

Her iki yazarın ortak katkı sağladığı aşamalar:

- Çevresel ve Ekonomik Etkiler: Çevresel ve ekonomik analizlerin yapılması ve yorumlanması
- Revizyon: Editör ve hakemler tarafından yapılan yorumların ele alınması ve düzeltmelerin yapılması.

CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest in this study.

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