Gazi Üniversitesi
Fen Bilimleri Dergisi
PART C: TASARIM VE TEKNOLOJİ

Gazi University
Journal of Science
PART C: DESIGN AND TECHNOLOGY

GU J Sci, Part C, 11(4): 1195-1208 (2023)

Optimization of Array Design in Photovoltaic Power Plants Using the Taguchi and ANOVA Analysis

Oğuz Kaan ÇİNİCİ*[1], Adem ACIR[1]

[1]*Gazi University, Faculty of Technology, Department of Energy Systems Engineering, Ankara/Türkiye*

Article Info

Research article
Received: 04/12/2023
Revision: 24/12/2023
Accepted: 24/12/2023

Keywords

ANOVA
Optimization
Photovoltaic (PV)
PVsyst
Taguchi

Makale Bilgisi

Araştırma makalesi
Başvuru: 04/12/2023
Düzeltme: 24/12/2023
Kabul: 24/12/2023

Anahtar Kelimeler

ANOVA
Optimizasyon
Fotovoltaik (FV)
PVsyst
Taguchi

Graphical/Tabular Abstract (Grafik Özet)

This study investigated eight PV solar power plant designs with varying array configurations and PV types. Using PVsyst simulations, the most suitable design was determined to be 3-portrai and bifacial PV. Taguchi and ANOVA analyzes highlighted the significant impact of PV type (65.27%) and array configuration (34.72%) on plant performance. / Bu çalışma, değişen dizi konfigürasyonlarına ve PV tiplerine sahip sekiz PV güneş enerjisi santrali tasarımını araştırmıştır. PVsyst simülasyonlarını kullanarak en uygun tasarımı 3-dikey ve çift yüzeyli PV olarak tespit edilmiştir. Taguchi ve ANOVA analizleri, PV tipinin (%65,27) ve dizi konfigürasyonunun (%34,72) tesis performansı üzerindeki önemli etkisini vurgulanmıştır.

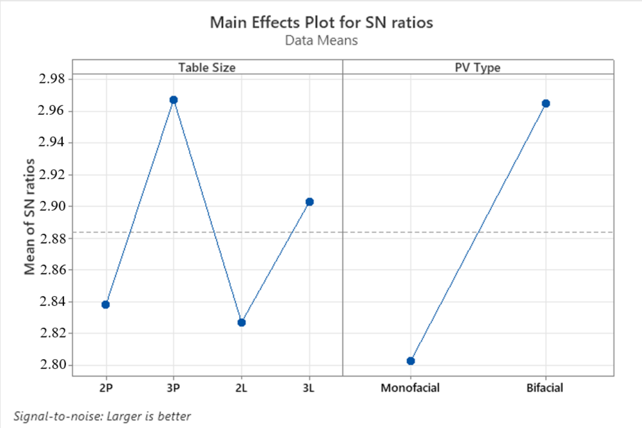

***Figure A**: Main effects plot for SN ratios /**Şekil A:** SN oranları için ana etki grafiği*

Highlights (Önemli noktalar)

- *Studied eight PV solar power plant designs with varied array configurations and PV types. / Çeşitli dizi konfigürasyonları ve PV tipleri ile sekiz PV güneş enerjisi santrali tasarımı üzerinde çalışıldı.*
- *Leveraged PVsyst software for simulations, evaluating E-grid, PR, and CO_2 emissions. / Simülasyonlar, E-şebeke, PR ve CO_2 emisyonlarının değerlendirilmesi için PVsyst yazılımından yararlanıldı.*
- *ANOVA analysis emphasized the significant impact of PV type (65.27%) and array configuration (34.72%) on plant efficiency. / ANOVA analizi, PV tipinin (%65,27) ve dizi konfigürasyonunun (%34,72) sistem verimliliği üzerindeki önemli etkisini vurguladı.*

***Aim (Amaç):** Optimize PV solar power plant efficiency through diverse design parameters. / Çeşitli tasarım parametreleriyle PV güneş enerjisi santralinin verimliliğini optimize edilmesi.*

***Originality (Özgünlük):** Diverse PV designs, configurations, and analyses pinpoint optimal efficiency-enhancing parameters for sustainability. / Çeşitli PV tasarımları, konfigürasyonları ve analizleri, sürdürülebilirlik için verimliliği artıran optimum parametreleri belirler.*

***Results (Bulgular):** Optimal PV plant design is 3-P with bifacial panels, emphasizing their substantial contributions to efficiency. / En uygun PV tesisi tasarımı, çift yüzeyli panellere sahip 3-P'dir tasarımıdır ve bu panellerin verimliliğe önemli katkılarını vurgular.*

***Conclusion (Sonuç):** Optimal PV solar plant design involves 3-P arrays and bifacial panels, emphasizing their substantial contributions to efficiency, sustainability, and performance variability. / Optimum PV güneş enerjisi santrali tasarımı, 3-P dizileri ve iki yüzeyli panelleri içerir ve bunların verimliliğe, sürdürülebilirliğe ve performans değişkenliğine önemli katkılarını vurgulamıştır.*

*Corresponding author, e-mail: oguzkaancinici@gazi.edu.tr
DOI: 10.29109/gujsc.1400053

GU J Sci, Part C, 11(4): 1195-1208 (2023)

Gazi Üniversitesi
Fen Bilimleri Dergisi
PART C: TASARIM VE TEKNOLOJİ

Gazi University
Journal of Science
PART C: DESIGN AND TECHNOLOGY

http://dergipark.gov.tr/gujsc

Optimization of Array Design in Photovoltaic Power Plants Using the Taguchi and ANOVA Analysis

Oğuz Kaan ÇİNİCİ*[1], Adem ACIR[1]

[1]*Gazi University, Faculty of Technology, Department of Energy Systems Engineering, Ankara/Türkiye*

Article Info

Research article
Received: 04/12/2023
Revision: 24/12/2023
Accepted: 24/12/2023

Keywords

ANOVA
Optimization
Photovoltaic (PV)
PVsyst
Taguchi

Abstract

Fossil fuels, predominant in fulfilling current energy demands, are implicated in global warming, prompting a global shift towards renewable energy sources. Among these, photovoltaic (PV) solar power plants have garnered significant attention, experiencing a rapid surge in installed power capacity. However, a notable drawback of PV solar power plants is their considerable spatial footprint, emphasizing the pivotal role of efficient space utilization and shading mitigation in their design. Notably, pitch distance, array design, and PV type emerge as critical parameters influencing the performance of these power plants during installation. In the present study, eight distinct PV solar power plant designs were conceptualized, incorporating four different PV array configurations (2P-3P-2L-3L) and two PV types (monofacial-bifacial), each with specified orientations (portrait-landscape). Other parameters were held constant across designs. Leveraging PVsyst software, simulations were conducted for each design, yielding crucial performance metrics, including the annual energy output delivered to the grid (E-grid), performance ratio (PR), and associated CO_2 emissions. Subsequently, a Taguchi analysis facilitated optimization based on these results. The outcome of this analysis identified the optimal PV array design as 3P and the optimal PV type as bifacial. Further insight was gained through an ANOVA analysis, revealing the substantial contributions of parameters to overall variability. Specifically, PV type exhibited a significant contribution of 65.27%, while PV array configuration contributed 34.72% to the observed variability in plant performance. These findings not only enhance the understanding of PV power plant design intricacies but also underscore the paramount significance of array design in achieving heightened efficiency and sustainability

Taguchi ve ANOVA Analizi Kullanılarak Fotovoltaik Enerji Santrallerinde Dizi Tasarımının Optimizasyonu

Makale Bilgisi

Araştırma makalesi
Başvuru: 04/12/2023
Düzeltme: 24/12/2023
Kabul: 24/12/2023

Anahtar Kelimeler

ANOVA
Optimizasyon
Fotovoltaik (FV)
PVsyst
Taguchi

Öz

Mevcut enerji taleplerinin karşılanmasında ağırlıklı olarak kullanılan fosil yakıtlar, küresel ısınmaya neden olmakta ve yenilenebilir enerji kaynaklarına doğru küresel bir yönelime yol açmaktadır. Bunlar arasında fotovoltaik (PV) güneş enerjisi santralleri büyük ilgi görmüş ve kurulu güç kapasitesinde hızlı bir artış yaşanmıştır. Bununla birlikte, PV güneş enerjisi santrallerinin kayda değer bir dezavantajı, fazla alan kaplamalarıdır; bu da tasarımlarında verimli alan kullanımının ve gölgelemenin azaltılmasının önemli rolünü vurgulamaktadır. Özellikle aralık mesafesi, dizi tasarımı ve PV tipi, bu enerji santrallerinin kurulum sırasında performansını etkileyen kritik parametreler olarak ortaya çıkıyor. Bu çalışmada, dört farklı PV dizi konfigürasyonunu (2P-3P-2L-3L) ve iki PV tipini (tek yüzlü-çift yüzlü) içeren ve her biri belirli yönelimlere (dikey-yatay) sahip sekiz farklı PV güneş enerjisi santrali tasarlanmıştır. Diğer parametreler tasarımlarda sabit tutuldu. PVsyst yazılımından yararlanılarak her tasarım için simülasyonlar gerçekleştirildi ve şebekeye iletilen yıllık enerji çıkışı (E-şebeke), performans oranı (PR) ve ilgili CO_2 emisyonları dahil olmak üzere önemli performans ölçümleri elde edildi. Daha sonra, bir Taguchi analizi bu sonuçlara dayalı optimizasyonu kolaylaştırdı. Bu analizin sonucu, en uygun PV dizisi tasarımını 3P ve en uygun PV tipini iki yüzeyli olarak tanımladı. ANOVA analizi yoluyla daha fazla bilgi elde edildi ve parametrelerin genel değişkenliğe önemli katkıları ortaya çıktı. Spesifik olarak, PV tipi %65,27'lik önemli bir katkı sergilerken, PV dizi konfigürasyonu tesis performansında gözlenen değişkenliğe %34,72 oranında katkıda bulunmuştur. Bu bulgular yalnızca PV enerji santrali tasarımının karmaşıklıklarının anlaşılmasını geliştirmekle kalmıyor, aynı zamanda yüksek verimlilik ve sürdürülebilirliğe ulaşmada dizi tasarımının büyük öneminin altını çiziyor.

*Corresponding author, e-mail: oguzkaancinici@gazi.edu.tr
DOI: 10.29109/gujsc.1400053

1. INTRODUCTION (GİRİŞ)

In the relentless pursuit of technological advancement and meeting the ever-increasing global energy demand, developing and deploying efficient and sustainable energy sources have become imperative. The pressing need for cleaner alternatives arises from the recognition that traditional energy sources, predominantly fossil fuels, are finite and pose significant environmental threats. The detrimental effects of fossil fuels on the environment have propelled the world into a paradigm shift, as underscored by international initiatives such as the Paris Climate Agreement [1]. Nations across the globe are now actively transitioning towards clean and renewable energy sources to mitigate climate change and build a sustainable future [2]. The growing consensus on the need for a green energy revolution drives substantial investments and research efforts toward renewable energy technologies. Among these technologies, photovoltaic (PV) solar power plants have emerged as a critical player in the global transition to clean energy [3], [4]. Harnessing the sun's abundant and renewable energy, PV power plants convert sunlight into electricity through the photovoltaic effect. As countries increasingly adopt renewable energy as a cornerstone of their energy portfolios, the efficiency and optimization of PV power plants become critical for realizing the full potential of solar energy [4]-[9].

The design and efficiency of PV power plants are pivotal considerations in the quest for optimal energy output. As these installations continue to scale up, the challenges associated with large-scale deployment become increasingly complex. Factors such as orientation, array design, and shading can significantly impact the performance of solar panels in a PV power plant. Consequently, researchers and engineers are turning to advanced simulation tools to model and analyze the behavior of PV systems under various conditions [10]-[14]. Software programs like PVsyst have become indispensable tools for simulating and optimizing PV systems. These programs allow for the detailed analysis of a range of parameters, including solar irradiance, temperature, and shading effects, enabling engineers to assess the performance of PV power plants in diverse environmental conditions. Simulation-based studies contribute valuable insights into system behavior, aiding in the refinement of design parameters and identifying optimization opportunities [15]. Among the numerous design considerations in PV power plants, the designs of arrays have particular significance. The optimization of array design is essential to mitigate challenges associated with large areas, shading effects, and other inefficiencies inherent in PV power plants.

Optimization ensures the system operates at peak efficiency, maximizing energy yield and minimizing operational costs. In this context, statistical methods such as the Taguchi method and Analysis of Variance (ANOVA) provide a systematic and structured approach to identifying and optimizing critical design parameters [16]-[20]. The Taguchi method, developed by Genichi Taguchi, is a robust statistical approach widely used for optimizing processes and designs. It enables engineers and researchers to identify the optimal combination of factors and their levels within a design space, minimizing variation and maximizing performance. This method is particularly valuable in the context of PV power plants, where a multitude of factors can influence overall efficiency [21],[22]. Complementing the Taguchi method, Analysis of Variance (ANOVA) is a statistical technique used to analyze a dataset's variability and quantify individual factors' contributions. ANOVA provides a rigorous statistical foundation for validating the significance of factors identified by the Taguchi method, enhancing the understanding of how different design parameters interact and impact overall system performance. There are many studies in the literature on design optimizations of PV power systems.

Kowsar et al. endorse floating solar photovoltaic (FSPV) systems as a remedy for challenges in large-scale ground-mounted photovoltaic power generation in densely populated areas. Utilizing PVsyst simulation tools, the study centers on a 50 MW FSPV power plant in a swamp region of an extremely densely populated country. Results indicate a competitive levelized cost of energy (LCOE) at US$0.051/kWh, notably lower than fossil fuel-based power plants at US$0.087/kWh in the case study country. The FSPV system exhibits environmental benefits, including reduced CO_2 emissions, diminished water evaporation, and preservation of biodiversity in swamp areas. This underscores the economic viability and positive environmental impact of FSPV as a promising alternative for energy production in densely populated regions with limited land resources [11].

Shan Hu et al. investigated the impact of dust accumulation on photovoltaic (PV) module efficiency, addressing the limitations of existing research that predominantly relied on field experiments and numerical simulations without comprehensive three-dimensional (3D) models. The study introduced proposed conditions for powder adsorption and developed a 3D simulation model to analyze settling factors. The authors optimized installation parameters through zonal clustering, revealing in a case study that a 17° angle and 0.5 m installation height maximized energy production in a category I zone. This underscores the significance of accounting for regional variations in optimizing PV module performance [10].

Tashtoush et al. aimed to create an environmentally sustainable living system for residential buildings by optimizing grid-connected and off-grid photovoltaic (PV) systems, focusing on reducing carbon emissions. The study centers on a typical residential building with ten apartments, employing a rooftop PV system modeled with BEopt and simulated using PVsyst software. After assessing various optimization scenarios, the study determines that a 10.6 kWh battery storage system, with a 5.7-year payback period and high net present value, covering over 95% of the electric load, is optimal. If widely adopted in Jordan, this model could potentially reduce carbon dioxide emissions by approximately 5.33 million metric tons, highlighting its environmental and economic benefits [12].

Irshad et al. assessed the performance of three PV technologies—monocrystalline silicon (m-Si), polycrystalline silicon, and amorphous silicon—with the goal of designing optimal PV-based hybrid systems. Following IEC 61724 metrics, m-Si demonstrated superior performance, with an annual array efficiency of 5.26 hours/day, a capacity factor of 14.31%, and a performance ratio of 83.9%. The recommended system configuration involves a 72.8 kW grid-connected PV and a 59.4 kW converter, with a total Net Present Cost (NPC) of $397,684, translating to $0.0493/kWh. Despite variations in sensitivity, the system proves resilient, offering valuable insights for researchers planning efficient PV-based hybrid systems [13].

Ihaddadene et al. highlights Algeria's commitment to green energy, particularly solar, utilizing the PVPA-1 calculation code. The case study investigates a 15 MW photovoltaic power plant in Tamanrasset, Algeria, for 2018. Results showcase PVPA-1's effectiveness in evaluating performance parameters, yielding reference, array, and final yields of 6 hours, 4.63 hours, and 4.58 hours, respectively. The tool identifies low system losses (0.052 hours) and peculiar behavior in subfield 9, impacting the overall power plant performance. In conclusion, PVPA-1 emerges as a robust tool for comprehensive performance analysis of photovoltaic installations [14].

Bayyiğit et al. compared monofacial and bifacial solar panels using PVsyst software in two solar power plants in Ankara. The study revealed that bifacial panels outperformed single-sided ones, showing a 13% higher average annual energy production. The albedo effect and CO_2 emissions were also analyzed, highlighting the environmental benefits of bifacial panels. The results suggest that promoting bifacial solar panel systems could be crucial for more efficient and sustainable energy production [23].

In this study aims to contribute to the ongoing discourse on optimizing PV power plant design by integrating the Taguchi method and ANOVA analysis. We use PVsyst software to analyze key design parameters related to array dimensions and PV types. The objective is to identify optimal configurations that maximize annual electrical energy production, and minimize CO_2 emissions, contributing to a more sustainable and efficient PV power plant design. Our study's originality lies in the synergy of the Taguchi method and ANOVA analysis, providing a systematic and statistically validated approach to optimize array design in photovoltaic power plants. This integrated methodology contributes a unique angle to the existing body of research in the field.

2. PVSYST SOFTWARE (PVSYST YAZILIMI)

Photovoltaic (PV) solar energy systems are gaining popularity as renewable energy sources in both residential and commercial settings. These systems convert sunlight into electrical energy using solar panels, and to enhance their efficiency, accurately modeling and simulating their performance under various conditions is crucial. A widely utilized software tool for this purpose is PVsyst, which PVsyst SA developed. It models and simulates the performance of photovoltaic solar energy systems by incorporating inputs such as weather data, system design parameters, and component specifications to predict system performance under diverse conditions. PVsyst is versatile, and capable of simulating both grid-connected and off-grid PV systems, accommodating different sizes and configurations [15], [22], [24], [26].

Design Optimization: PVsyst is instrumental in optimizing PV system design by simulating performance under varying configurations. The software evaluates different designs, including changes in panel orientation, tilt angle, and shading, to identify the optimal design for a specific location and application.

Performance Analysis: PVsyst facilitates the analysis of existing PV systems, comparing actual and predicted performance data to pinpoint discrepancies or issues. This analysis aids in identifying areas for improvement and optimizing overall system performance.

Financial Analysis: PVsyst supports financial analysis by estimating energy production and revenue generation. The software calculates vital financial metrics such as payback period, internal rate of return, and net present value, providing insights into the financial viability of a project.

Energy Yield Prediction: PVsyst predicts the energy yield of a PV system under different conditions, considering factors like weather patterns, shading, and system design. It estimates energy generation for a specific location, aiding in effective system planning.

System Configuration: PVsyst creates the panel array and adjusts panel slopes depending on the system's power. It fine-tunes both panel tilt and azimuth angles, with the azimuth angle representing the angle between the south/north and the collector plane. Inverter selection aligns with the created string, and the simulation is conducted after the system setup is complete [15].

3. PROJECT DESIGN (PROJE TASARIMI)

In the realm of photovoltaic (PV) power system design, the efficacy of the system is linked to various parameters, including location, PV and inverter type, array design, and array stand inclination angle. This study focuses on assessing the impact of these parameters on system performance, mainly through exploring four distinct array designs utilizing both monofacial and bifacial PVs. The objective is to discern the optimum array design for enhanced PV power system efficiency. Four different PV arrays were used according to the number and orientation of PV: double portrait (2P), triple portrait (3P), double landscape (2L), and triple landscape (3L). The levels and factors selected in the simulations are listed in Table 1.

Table 1. Factors and levels used in the simulations (Simülasyonlarda kullanılan faktörler ve seviyeler)

Parameters	Levels			
	1	2	3	4
Array Size	2P	3P	2L	3L
PV Type	Monofacial	Bifacial		

As seen in Table 2, a total of eight PV power systems were designed and simulated using PVsyst software. Pitch distance was calculated for four different array designs. Each system was configured with an installed power capacity of 500 kW, while keeping other parameters constant. The simulations were carried out in Karapınar, Türkiye, leveraging meteorological data obtained from PVGIS. Meteorological data in the coordinates are given in Table 3.

Table 2. L8(4^1 2^4) array: Taguchi design utilized in this study. dizisi: (L8(4^1 2^4) bu çalışmada kullanılan Taguchi tasarımı)

Design	Array Size	PV Type
Design-1	2P	Monofacial
Design-2	2P	Bifacial
Design-3	3P	Monofacial
Design-4	3P	Bifacial
Design-5	2L	Monofacial
Design-6	2L	Bifacial
Design-7	3L	Monofacial
Design-8	3L	Bifacial

Table 3. Monthly data of coordinates selected for installation [26] (Kurulum için seçilen koordinatların aylık verileri)

	Global horizontal irradiation (kWh/m²)	Horizontal diffuse irradiation (kWh/m²)	Temperature (°C)	Wind velocity (m/s)	Relative humidity (%)
January	56.8	27.4	1.2	3.41	79.1
February	103.8	37.7	5.2	1.90	70.2
March	127.1	58.2	8.1	3.42	69.6
April	174.3	64.8	12.0	2.61	67.8
May	217.5	75.1	20.0	2.88	46.1
June	241.7	62.1	24.9	3.04	42.2
July	253.4	58.9	27.7	3.14	36.9
August	228.8	55.6	24.9	3.90	39.0
September	175.0	48.1	24.3	2.17	41.8
October	133.4	40.9	12.4	2.95	58.7
November	81.2	30.4	3.3	2.36	65.6
December	62.1	27.1	1.6	2.52	82.2
Year	1855.0	586.2	13.8	2.9	58.3

The spatial arrangement of the shed is predominantly defined by three key parameters: PV array width (W), pitch (Pitch), and tilt angle (α), as illustrated in Figure 1. In this context, the shading limit angle (β) is identified as the angle at which a shadow initiates on the adjacent shed, as depicted in Figure 1.

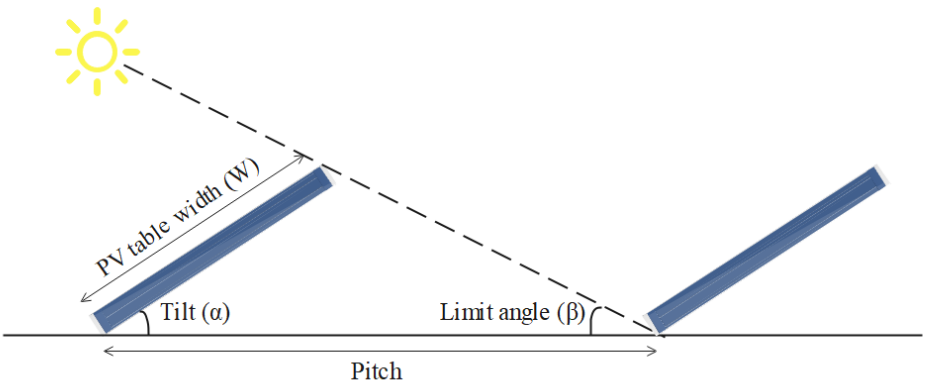

Figure 1. Sheds scheme (Işınım Şeması)

It is noteworthy that no universally optimal value exists for this angle. However, conventionally, the worst-case scenario (December 21) is considered to minimize mutual shadings. To ensure the absence of shading on the solar panel plane, the pitch is calculated using Equation (1) for a specified shading limit angle [28].

$$Pitch=W(\cos\alpha+\sin\alpha/\tan\beta) \quad (1)$$

Pitch distance was calculated for four different array designs. Each system was configured with an installed power capacity of 500 kW, while keeping other parameters constant. Array width and pitch distances for each design are calculated and given in Table 4. These values were used in the simulation.

Table 4. Array width and pitch distances for each design (Her tasarım için dizi aralığı ve adım mesafeleri)

Design	Array Width, W (m)	Pitch (m)
Design-1	4.39	8.47
Design-2	4.39	8.47
Design-3	6.6	12.74
Design-4	6.6	12.74
Design-5	2.22	4.28
Design-6	2.22	4.28
Design-7	3.35	6.46
Design-8	3.35	6.46

A critical consideration in the design of a photovoltaic (PV) system is the ground cover ratio (GCR), denoting the proportion of the modules' sensitive area to the total ground area occupied by the PV system. Notably, the "real" ground cover ratio can alternatively be expressed as the ratio of width to pitch. This presentation aligns with the design of the PV system, as it is based on shed parameters rather than the initial available area. This approach is deemed more pertinent as it incorporates shed characteristics, ensuring a more accurate representation of the actual ground cover ratio in the PV system design [28].

The disposition of solar panels was investigated considering two distinct arrangements: portrait and landscape orientations. It is imperative to underscore the significance of shading in optimizing a photovoltaic (PV) array, given that the beam component impacts the electrical shading dynamics within the system. Consequently, this study conducted numerous simulations, systematically varying the width of the PV array for two different PV types under fixed tilt (α=37°), fixed limit angle (β=28°), and fixed azimuth angle (0°) conditions. This approach facilitated a comprehensive understanding of the shading effects on each case independently.

The determination of the optimal tilt for maximizing energy production typically assumes alignment with the site latitude [29]. In the context of fixed-tilt systems, the annual energy yield and Performance Ratio (PR) are markedly influenced by both the pitch and plane tilt. These factors are pivotal in shaping incident irradiation and shading patterns within the collector plane. It is essential to note that PR, denoting the ratio of effectively produced energy to the energy generated under nominal efficiency conditions (Standard Test Conditions, STC), is highly contingent on both pitch and plane tilt configurations.

3.1. PV and inverter selection (PV ve invertör seçimi)

To conduct a comparative analysis, monofacial and bifacial modules with commensurate specifications were meticulously chosen, with preference given to Trina Solar as the brand. The pertinent characteristics of the selected modules are presented in Table 5.

Tablo 5. Technical specifications of monofacial and bifacial PV modules used in the study (Çalışmada kullanılan tek yüzeyli ve çiftyüzeyli PV modüllerin teknik özellikleri)

	Monofacial	**Bifacial**
Brand	Trina Solar	Trina Solar
Model	TSM-DE18M–(II)–500	TSM-DEG18MC-20-(II)-500 Bifacial
Nominal power	500 Wp	500 Wp
Cell	75x2	75x2
Length	2176 mm	2256 mm
Width	1098 mm	1133 mm
Thickness	35 mm	30 mm
Weight	26.3 kg	32.3 kg
Module area	2,389 m²	2.556 m²
Short circuit current (I_{sc})	12.28 A	13.92 A
Open circuit voltage (V_{oc})	51.7 V	50.3 V
Maximum power point current (I_{mpp})	11.69 A	13.04 A
Maximum power point voltage (V_{mpp})	42.8 V	41.8 V
Temperature coefficient	– 0.35 %/◦C	– 0.34 %/◦C

Both panels were positioned at a standardized height of 1.5 meters above the ground. The ground albedo effect for the bifacial panel was established at 0.6, a value achievable through the application of white paint or cement [30]. Huawei Technologies, one of the important players in the solar energy industry, was preferred in the inverter selection. Considering its suitability for the number and type of panels, the SUN2000-55KTL-H2 model, which has eight units of 55 kW AC output power and an operating voltage range of 600 to 1450 V, was deemed suitable.

Integral to the design process in PVsyst simulation is the number of modules and chains, which are pivotal parameters influencing optimal system performance. These variables are intricately interconnected and necessitate judicious selection to ensure the efficacy of the design. The number of serial modules denotes the quantity of arrays where modules are serially connected. In PVsyst, this number is determined by meticulous attention to the congruence between the operating voltage of the modules and that of the inverter. Augmenting the number of series modules has the potential to amplify power output, but it is imperative to avoid exceeding the inverter's operating voltage. Concurrently, the chain count signifies the number of parallel-connected threads. While escalating the number of chains enhances total power output, it also increases total current. Hence, careful consideration of the inverter's input current limits is crucial. Furthermore, reducing the number of threads can enhance module performance, especially in challenging conditions such as shading. In light of these considerations, the number of serial modules was established at 20, while the number of chains was set at 50.

4. OPTIMIZATION ANALYSIS (OPTİMİZASYON ANALİZİ)

The implementation of optimization analyses is pivotal for advancing the understanding of the intricate relationship between the control parameters inherent in a process and the corresponding quality parameters [30]. Within the scholarly discourse, researchers employ diverse optimization methodologies tailored to the specific objectives of their investigations. The primary objective of our study was to discern the most optimal combination of control parameters that influence quality characteristics. Accordingly, we opted for the Taguchi method, renowned for its simplicity, efficiency, and systematic approach, facilitating the derivation of results through a minimized number of trials within the shortest possible timeframe. Additionally, the contribution rates of these parameters were elucidated through the application of Analysis of Variance (ANOVA) [31],[32].

4.1. Taguchi method (Taguchi yöntemi)

The Taguchi method stands as a widely employed statistical approach for optimizing factors influencing the performance characteristics of a given process or system. This method effectively yields results from minimal trials, thereby delineating the significance and hierarchy of control parameters. Moreover, it identifies the most influential parameter and determines the optimal level for each parameter within the system. Notably, the Taguchi method tests combination pairs rather than exhaustively testing all potential combinations. Over the past two decades, it has found widespread application across various engineering disciplines and beyond [33],[34].

The Taguchi method comprises vital components such as an orthogonal array, signal-to-noise ratio (S/N or SNR), response table, and response graph, also known as Main Effect Analysis (MEA). The highest SNR value for each parameter indicates the optimal level for that parameter, while the highest primary impact value signifies the parameter's most significant influence on system performance. Subsequently, a Mean Effective Plot (response graph) for SNRs is generated using the optimum control factors derived from the response table, allowing for an in-depth analysis of the impact of control factors on performance [35],[36].

The analysis of SNR incorporates three distinct performance characteristics: larger-is-better, nominal-is-better, and smaller-is-better. In this context, the preference was given to 'larger-is-better' performance characteristics, and Equation (2) was utilized to calculate SNR values, facilitating a comprehensive assessment of the system's performance [31],[34],[35],[36].

$$\frac{S}{N} = -10\log\left(1/n \sum_{i=1}^{n} \frac{1}{{y_i}^2}\right) \quad (2)$$

4.2. Analysis of variance (ANOVA) (Varyans analizi)

The Analysis of Variance (ANOVA), a statistical method, serves as a decision-making tool utilized to discern the proportional contribution of each parameter to the overall performance of a system. It is instrumental in determining the significance of each parameter's impact on the response, thereby validating the outcomes derived from the Taguchi method [31],[32].

Within the scope of this study, the ANOVA method is employed to elucidate the influence of each parameter on the uniformity of annual energy output delivered to the grid (E-Grid), Performance Ratio (PR), and the saved CO_2 emissions. The statistical significance level is set at 0.05, corresponding to a 95% confidence level. Equations (3), (4), (5), (6), and (7) are utilized to derive critical indicators of the ANOVA method, including the sum of squares (SS), contribution ratio (CR), degrees of freedom

(DOF), mean of squares (MS), and F-values for each factor. This comprehensive analysis aids in comprehending the individual and collective impacts of the parameters on the system's performance [31]-[38].

$$SS_i = \sum_{i=1}^{n}(\hat{y}_i - \bar{y})^2 \quad (3)$$

Where, $\hat{y}_i$ is the i-th response value, $\bar{y}$ is the mean response value.

The contribution ratio (CR) is defined as the ratio of the sum of squared deviations to the total sum of squared deviations Eq. (4).

$$CR_i = \frac{SS_i}{SS_T} \quad (4)$$

The corresponding degrees of freedom are as follows Eq. (5):

$$DOF_T = \sum_{i=1}^{n_f}(L_i - 1) + DOF_{error} \quad (5)$$

The corresponding mean of squares are as follows Eq. (6):

$$MS_i = \frac{SS_i}{DOF_i} \quad (6)$$

The F-factor, which reflects the statistical reliability of the results, is given by the ratio of the parameter's mean square to the mean square error Eq. (7).

$$F_i = \frac{MS_i}{MS_{error}} \quad (7)$$

5. RESULTS (BULGULAR)

Based on the outcomes generated by PVsyst, the application of the Taguchi method involves the establishment of a pertinent model through rigorous statistical analysis. The primary aim of this method is to discern the optimal values for the array in photovoltaic (PV) systems. The simulation design, as depicted in Table 6, is formulated using Signal-to-Noise (S/N) ratios derived from the Taguchi method. Each row in this design encapsulates a distinct combination of various parameter levels. The control parameters are systematically allocated to the columns, and the output responses, along with their corresponding S/N ratio values, are computed and likewise assigned to the columns. This systematic representation facilitates a comprehensive analysis of the relationships between control parameters and system responses in PV systems.

Table 6. Simulation design with SN ratio (SN oranlı simülasyon tasarımı)

Design	Array Size	PV Type	E-Grid (MWh)	PR	Saved CO_2 Emissions (tons)	S/N Ratios
Design-1	2P	Monofacial	841.44	0.793	9818.806	2.7567
Design-2	2P	Bifacial	856.43	0.808	10009.61	2.9194
Design-3	3P	Monofacial	854.04	0.805	9979.271	2.8871
Design-4	3P	Bifacial	869.11	0.82	10177.427	3.0475
Design-5	2L	Monofacial	839.96	0.792	9799.972	2.7457
Design-6	2L	Bifacial	855.28	0.807	9994.947	2.9087
Design-7	3L	Monofacial	847.37	0.799	9894.26	2.8221
Design-8	3L	Bifacial	862.81	0.814	10090.869	2.9837

Given that the primary objective of the current investigation is to maximize E-Grid, PR, and Saved CO_2 Emissions, the "Larger the better" criterion is adopted. Consequently, the Signal-to-Noise (S/N) ratio is computed for the response variable, wherein a higher value indicates superior performance.

The response table in Table 4 delineates the S/N ratio for various levels of the critical factors under consideration. Adhering to the principles of the Taguchi method, the optimum S/N ratio is observed at the second level of Array Size and PV type, as detailed in Table 7 and visually represented in Figure 2. Consequently, the highest values for E-Grid (869.11 MWh), PR (0.82), and Saved CO_2 emissions (10177.427 tons) were realized in Design-4. This outcome signifies the optimal configuration that aligns with the goal of maximizing the specified performance metrics.

Table 7. Response table for means (Yanıt tablosu)

Level	Array Size	PV Type
1	3588	3573
2	3647	3643
3	3582	
4	3616	
Delta	65	70
Rank	2	1

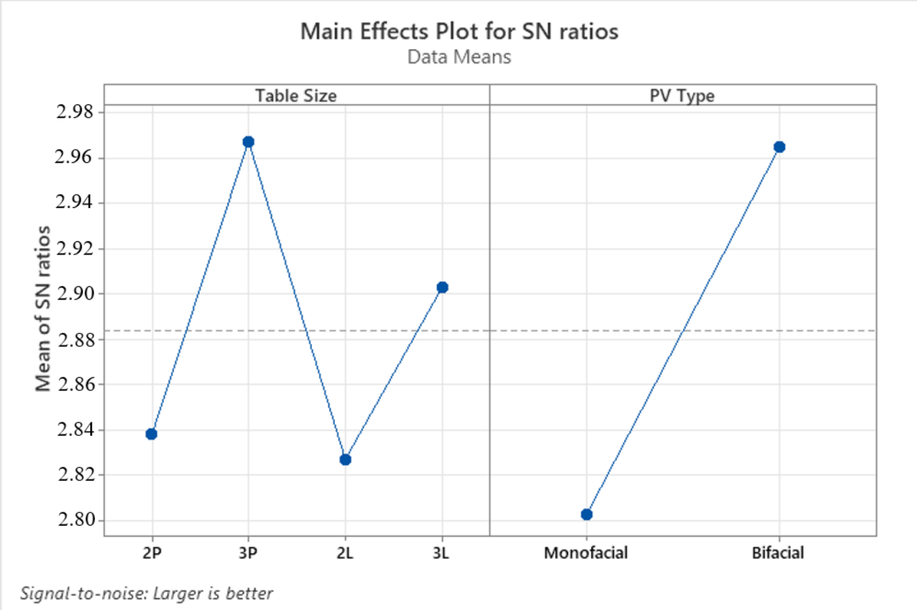

Figure 2. Main effects plot for SN ratios (SN oranları için etki grafiği)

As a statistical methodology, the analysis of variance (ANOVA) furnishes a comprehensive framework for examining the outcomes associated with the response variable, as delineated in Table 6. This analytical endeavor showcases meticulous precision, underscored by a substantial R-squared value of 99.93% and an adjusted R-square value of 99.98%. These metrics not only attest to the efficacy of the chosen model but also signify its robust fitting to the observed data, thereby reflecting a commendable degree of model accuracy.

Moreover, the values enlisted in Table 8 assume heightened statistical significance, with a pivotal emphasis on maximizing F-values and minimizing P-values, precisely attaining a threshold below 0.005. This nuanced criterion substantiates the steadfastness of the statistical inferences derived from the ANOVA analysis, affirming the appropriateness and reliability of the selected model in elucidating the variability observed in the response variable. In essence, the ANOVA results provide a nuanced understanding of the statistical relationships inherent in the examined data, fortifying the robustness and credibility of the analytical findings.

Table 8. Analysis of variance (Varyans analizi)

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Array Size	3	245.990	34.72%	245.990	81.997	3701.89	0.0000075
PV Type	1	462.384	65.27%	462.384	462.384	20875.13	0.0000007
Error	3	0.066	0.01%	0.066	0.022		
Total	7	708.441	100.00%				

Figure 3 depicts the residual plots corresponding to distinct parameters under investigation. The residual plot against predicted values manifests a stochastic distribution of the dispersed points, while the residual plot against run number exhibits an absence of discernible patterns. Additionally, the normal probability plot aligns consistently along the linear axis. Moreover, the residual errors concerning fits and order are quantified at 0.117, indicative of the precision of the model and thereby affirming its appropriateness. The contribution of the PV array size parameter is elucidated at 34.72%, with the PV type parameter exhibiting a substantial contribution of 65.27% to the observed variability in E-Grid. This underscores the notable influence of these parameters on the response variable. In summary, the residual analyses, precision metrics, and parameter contributions collectively underscore the efficacy and accuracy of the model in elucidating the intricate relationships between the considered factors and the response variable. These findings substantiate the model's suitability and its capacity to accurately represent the simulation runs of the response variables.

a) b)

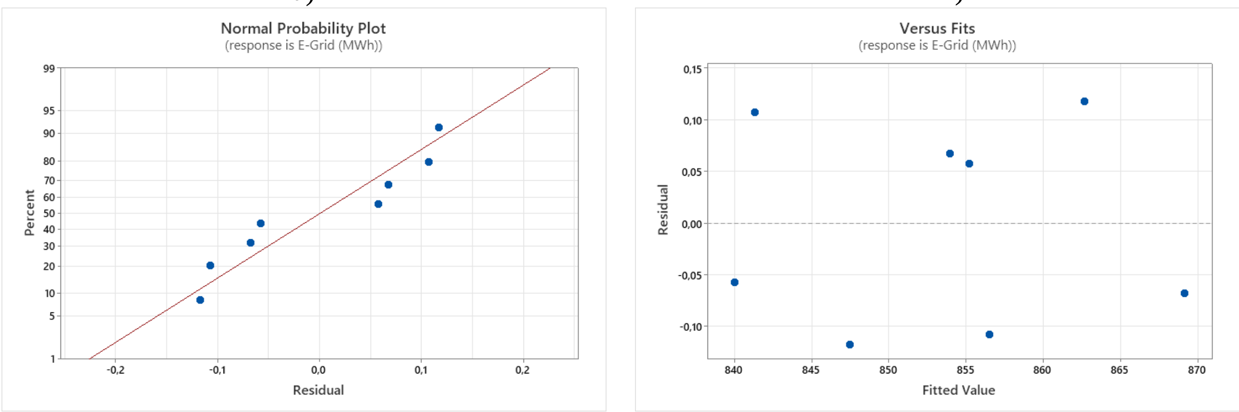

Figure 3. Residual figures for E-Grid a) normal probability plot, b) residual versus predicted (E-Şebeke için artık rakamlar a) normal olasılık grafiği, b) artık ve tahmin edilenler)

Figure 4 illustrates the E-Grid and saved CO_2 emissions values for each design configuration. The maximum E-Grid value, quantified at 869.11 MWh, was attained in Design-4 (3P-Bifacial), while the minimum E-Grid value, amounting to 839.96 MWh, was recorded in Design-5 (2L-Monofacial). Likewise, the highest saved CO_2 emissions were computed in Design-4, totaling 10177.427 tons, while the lowest saved CO_2 emissions, amounting to 9799.972 tons, were observed in Design-5. Furthermore, an evident positive correlation is discernible between the E-Grid and saved CO_2 emissions outputs. This observation implies that variations in E-Grid values coincide with consistent trends in saved CO_2 emissions across the diverse design configurations.

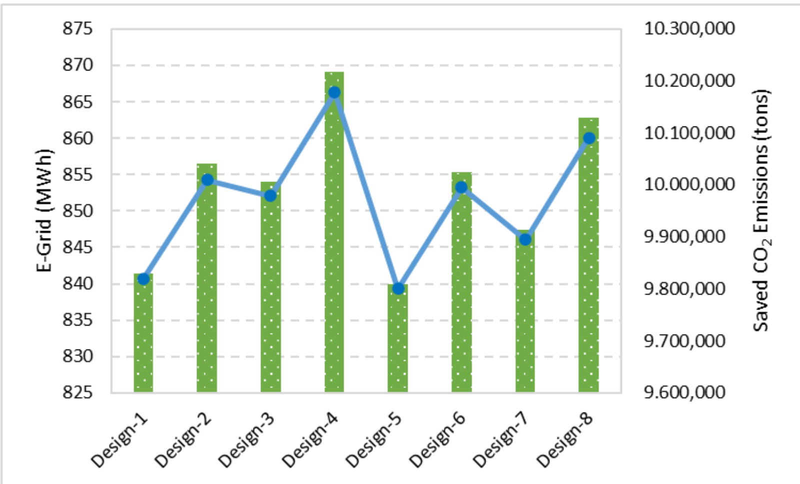

Figure 4. E-Grid and saved CO_2 emissions values for designs (Tasarımlar için E-Grid ve tasarruf edilen CO_2 emisyon değerleri)

Figure 5 displays the performance ratio (PR) values for all designs. The highest PR, calculated at 0.82, is observed in Design-4 (3P-Bifacial), while the lowest PR, computed at 0.792, is found in Design-5 (2L-Monofacial). Additionally, it is evident that the PR values exhibit a positive correlation with the outputs of E-Grid and saved CO_2 emissions. This observation suggests that variations in PR values align consistently with trends in both E-Grid and saved CO_2 emissions across the entire spectrum of design configurations.

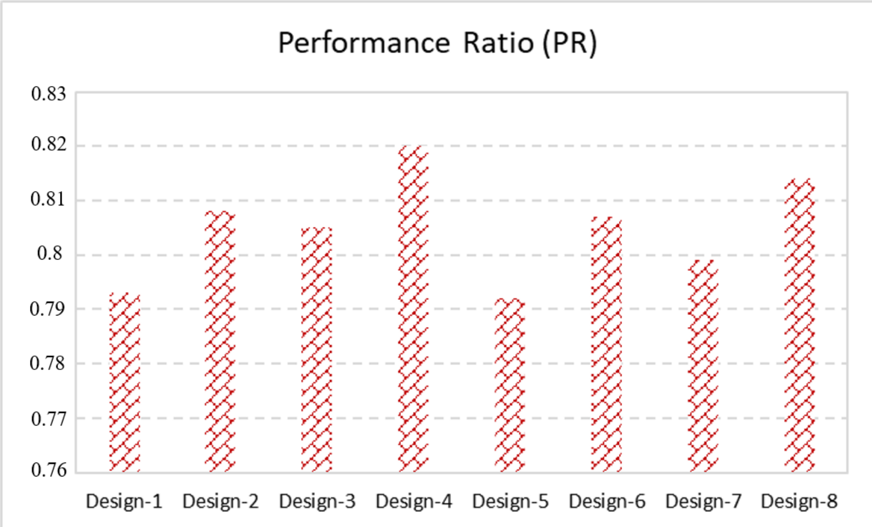

Figure 5. Performance ratio (PR) values for designs (Tasarımlara ilişkin performans oranı (PR) değerleri)

Previous research explored the performance rates of diverse PV array panel designs through simulation studies. Literature reviews have documented performance rates for various PV array designs, as outlined in Table 9. It is evident that the outcomes of our study align with those reported in existing literature.

Table 9. Comparison of the performance ratio results of this study with the literatüre (Bu çalışmanın performans oranı sonuçlarının literatürle karşılaştırılması)

Reference	Location	Average final yield (kWh/kWp/day)	Rated Capacity (kWp)	Performance ratio (%)
Present study	Konya, Türkiye	23,8	500	82
Emziane and Ali [39]	Abu Dhabi	5.1	111.4	80
Sharma and Chandel [40]	Khatar-Kalan, India	2.23	190	74
Anang et al. [41]	Terengganu, Malaysia	3.78	7.8	71
Okello et al. [42]	Eastern Cape, South Africa	4.9	3.2	84

6. CONCLUSIONS (SONUÇLAR)

In conclusion, the optimization of array design in photovoltaic power plants, as explored through the Taguchi and ANOVA analyses, has yielded valuable insights into the factors influencing the performance of these systems. The comprehensive utilization of these statistical methodologies has allowed for a nuanced understanding of the interplay between critical parameters, such as Array Size and PV Type, and the performance metrics, including E-Grid, saved CO_2 emissions, and Performance Ratio (PR).

• The Taguchi method efficiently optimized design configurations, emphasizing the significant impacts of Array Size and PV Type on the E-Grid. The precise model, with low residual errors and well-distributed plots, affirms conclusion reliability. ANOVA analysis validated statistical significance, providing a robust framework for assessing individual parameter contributions.

• Notably, the positive correlation observed between PR values and the outputs of E-Grid and saved CO_2 emissions further highlights the interconnectedness of these performance metrics. This insight is crucial for designing photovoltaic power plants that maximize energy production and contribute to environmental sustainability.

• Consequently, the highest values for E-Grid (869.11 MWh), PR (0.82), and Saved CO_2 emissions (10177.427 tons) were realized in Design-4 (3P-Bifacial).

• The highest PR, calculated at 0.82, is observed in Design-4, while the lowest PR, computed at 0.792, is found in Design-5 (2L-Monofacial).

• The highest saved CO_2 emissions were computed in Design-4, totaling 10177.427 tons, while the lowest saved CO_2 emissions, amounting to 9799.972 tons, were observed in Design-5.

In summary, the combined application of the Taguchi and ANOVA analyses has empowered the optimization of array design in photovoltaic power plants, offering a systematic approach to achieving enhanced performance. The findings of this study contribute valuable knowledge to the field of renewable energy system design and underscore the importance of array design in maximizing the efficiency and sustainability of photovoltaic power plants.

ACKNOWLEDGMENTS (TEŞEKKÜR)

If the study was supported by a research institution or fund, the name of the supporting institution/organization and the project number should be written. / Çalışma araştırma kurumu veya fonu tarafından desteklenmiş ise destek sağlayan kurum/kuruluş adı ve proje numarası yazılmalıdır.

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

AUTHORS' CONTRIBUTIONS (YAZARLARIN KATKILARI)

***Oğuz Kaan ÇİNİCİ*:** He made the design and simulations, analyzed the results and wrote the article.

Tasarım ve simülasyonları yapmış, sonuçlarını analiz etmiş ve makalenin yazım işlemini gerçekleştirmiştir.

***Adem ACIR*:** He analyzed the simulation results and checked the article.

Simülasyon sonuçlarını analiz etmiş ve makalenin kontrolünü gerçekleştirmiştir.

CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest in this study.

Bu çalışmada herhangi bir çıkar çatışması yoktur.

REFERENCES (KAYNAKLAR)

[1] Tedeschi, M., Foglia, M., Bouri, E., and Dai, P., “How does climate policy uncertainty affect financial markets? Evidence from Europe” Economics Letters, vol. 234, p. 111443, 2023.
[2] Mahmood, N. S., Ajmi, A. A., Sarip, S., Kaidi, H. M., Suhot, M. A., Jamaludin, K. R., and Talib, H. H. A., “Modeling energy management sustainability: Smart integrated framework for future trends,” Energy Reports, vol. 8, pp. 8027-8045, 2022.
[3] Crespi, E., Colbertaldo, P., Guandalini, G., and Campanari, S., “Design of hybrid power-to-power systems for continuous clean PV-based energy supply,” International Journal of Hydrogen Energy, vol. 46, no.26, pp. 13691-13708, 2021.
[4] Mehmood, A., Ren, J., and Zhang, L., “Achieving energy sustainability by using solar PV: System modelling and comprehensive techno-economic-environmental analysis,” Energy Strategy Reviews, vol. 49, p. 101126, 2023.
[5] Liu, D., Kang, Y., Ji, X., Zhang, X., and Wu, Y., “Bi-objective Pareto optimization for clustering-based hierarchical power control in a large-scale PV power plant,” Sustainable Energy Technologies and Assessments, vol. 57, p. 103283, 2023.
[6] Veríssimo, P. H. A., Campos, R. A., Guarnieri, M. V., Veríssimo, J. P. A., Do Nascimento, L. R., and Rüther, R., "Area and LCOE Considerations in Utility-scale, Single-axis Tracking PV Power Plant Topology Optimization." Solar Energy, vol. 211, pp. 433-445, 2020.
[7] Safarzadeh Ravajiri, E., Jalali, A., and Houshfar, E., "Multi-objective Optimization and 4E Analysis of an Integrated System Based on Waste-to-energy, Solar PV, Power-to-gas, and HDH-RO Desalination." Energy Conversion and Management, vol. 277, p. 116677, 2023.
[8] Mateo Romero, H. F., Hernández-Callejo, L., González Rebollo, M. Á., Cardeñoso-Payo, V., Alonso Gómez, V., Morales Aragonés, J. I., and Moyo, R. T., "Optimized Estimator of the Output Power of PV Cells Using EL Images and I–V Curves." Solar Energy, vol. 265, p. 112089, 2023.
[9] Cox, J. L., Hamilton, W. T., and Newman, A. M., "Parametric Analysis on Optimized Design

of Hybrid Solar Power Plants." Solar Energy, vol. 252, pp. 195-217, 2023.

[10] Hu, S., Wu, Z., Li, S., Xu, B., Wu, J., and Liu, W., "Research on Dust Deposition of PV Modules Based on Three-dimensional Numerical Simulation and Its Application in Installation Parameter Optimization." Journal of Cleaner Production, vol. 423, p. 138743, 2023.

[11] Kowsar, A., Hassan, M., Rana, M. T., Haque, N., Faruque, M. H., Ahsan, S., and Alam, F., "Optimization and Techno-economic Assessment of 50 MW Floating Solar Power Plant on Hakaluki Marsh Land in Bangladesh., "Renewable Energy, vol. 216, p. 119077, 2023.

[12] Tashtoush, B., Alalul, K., and Najjar, K. "Designing Sustainable Living: Optimizing on/Off-Grid PV Systems for Carbon-Reduced Residential Buildings in Jordan." Energy and Buildings, vol. 297, p. 113441, 2023.

[13] Irshad, A. S., Ludin, G. A., Masrur, H., Ahmadi, M., Yona, A., Mikhaylov, A., Krishnan, N., and Senjyu, T., "Optimization of Grid-photovoltaic and Battery Hybrid System with Most Technically Efficient PV Technology After the Performance Analysis." Renewable Energy, vol. 207, pp. 714-730, 2023.

[14] Ihaddadene, R., Jed, M. E. H., and Ihaddadene, N., "Assessing the Effectiveness of a PV Power Plant and Its Subfields in Algeria: Case Study Tamanrasset." Energy for Sustainable Development, vol. 77, p. 101348, 2023.

[15] Ashok Kumar L., Indragandhi V., and Uma Maheswari Y., "PVSYST." Software Tools for the Simulation of Electrical Systems, Academic Press, ch. 9, pp. 349-392, 2020.

[16] Çinici, O. K., Canlı, M. E., Çakıroğlu, R., and Acır, A., "Optimization of Melting Time of Solar Thermal Energy Storage Unit Containing Spring Type Heat Transfer Enhancer by Taguchi Based Grey Relational Analysis." Journal of Energy Storage, vol. 47, p. 103671, 2022.

[17] Qasim, A., Nisar, S., Shah, A., Khalid, M. S., and Sheikh, M. A., "Optimization of Process Parameters for Machining of AISI-1045 Steel Using Taguchi Design and ANOVA." Simulation Modelling Practice and Theory, vol. 59, pp. 36-51, 2015.

[18] Çakıroğlu, Ramazan, and Adem Acır., "Optimization of Cutting Parameters on Drill Bit Temperature in Drilling by Taguchi Method." Measurement, vol. 46, no. 9, pp. 3525-3531, 2013.

[19] Sahoo, S., Dalei, R. K., Rath, S. K., and Sahu, U. K., "Selection of PSO Parameters Based on Taguchi Design-ANOVA- ANN Methodology for Missile Gliding Trajectory Optimization." Cognitive Robotics, vol. 3, pp. 158-172, 2022.

[20] Acır, A., Canlı, M. E., Ata, İ., and Çakıroğlu, R., "Parametric Optimization of Energy and Exergy Analyses of a Novel Solar Air Heater with Grey Relational Analysis." Applied Thermal Engineering, vol. 122, pp. 330-338, 2017.

[21] Hong, Y., Beltran, A. A., and Paglinawan, A. C., "A Robust Design of Maximum Power Point Tracking Using Taguchi Method for Stand-alone PV System." Applied Energy, vol. 211, pp. 50-63, 2018.

[22] Çinici, O. K., Karaca, B., and Acır, A., "Comparison Study in Terms of The Results of Photovoltaic Solar Energy Systems Designed with PVsyst and MATLAB Simulink Software." Politeknik Dergisi, vol. 26, no. 4, pp. 1635-1649, 2023.

[23] Kazemian, A., Parcheforosh, A., Salari, A., and Ma, T., "Optimization of a Novel Photovoltaic Thermal Module in Series with a Solar Collector Using Taguchi Based Grey Relational Analysis." Solar Energy, vol. 215, pp. 492-507, 2021.

[24] Bayyiğit, A., Çinici, O. K., and Acir, A., "Tek yüzeyli ve çift yüzeyli fotovoltaik panellerin performans analizi." Gazi University Journal of Science Part C: Design and Technology, vol. 11, no. 2, pp. 407-420, 2023.

[25] T. Khatib, A. Mohamed, and K. Sopian, "A software tool for optimal sizing of PV systems in Malaysia," Modelling and Simulation in Engineering, vol. 1, p. 969248, 2012.

[26] "PVsyst – Logiciel Photovoltaïque." https://www.pvsyst.com/ (accessed Nov. 29, 2023).

[27] "Photovoltaic Geographical Information System." https://www.pvsyst.com/help/meteo_source_pvgis.htm/ (accessed Nov. 29, 2023).

[28] Silva, Miguel, Rui Castro, and Mário Batalha., "Technical and Economic Optimal Solutions for Utility-Scale Solar Photovoltaic Parks." Electronics, vol. 9, no. 3, p. 400, 2020.

[29] Prasad M. and Prasad R., "Bifacial vs monofacial grid-connected solar photovoltaic for small islands: A case study of Fiji." Renew Energy, vol. 203, pp. 686–702, 2023.

[30] Fan, W., Kokogiannakis, G., and Ma, Z., "A Multi-objective Design Optimisation Strategy for Hybrid Photovoltaic Thermal Collector (PVT)-solar Air Heater (SAH) Systems with Fins." Solar Energy, vol. 163, pp. 315-328, 2018.

[31] Omidi, B., Rahbar, N., Kargarsharifabad, H., and Poolaei Moziraji, Z., "Performance Evaluation of a Solar Desalination-hot Water System Using Heat Pipe Vacuum Tube Parabolic Trough Solar Collector – An Experimental Study with Taguchi Analysis." Energy Conversion and Management, vol. 292, p. 117347, 2023.

[32] Xie, B., Peng, Q., E, J., Tu, Y., Wei, J., Tang, S., Song, Y., and Fu, G., “Effects of CO addition and multi-factors optimization on hydrogen/air combustion characteristics and thermal performance based on grey relational analysis.” Energy, vol. 255, p. 124573, 2022.

[33] Ata İ. and Acır A, “Hava akışkanlı güneş kollektöründe ısı transferi iyileştirmesine etki eden parametrelerin taguchi metodu ile optimizasyonu.” Politeknik Dergisi, vol. 23, no. 2, pp. 527-535, 2020.

[34] Xie, B., Peng, Q., E, J., Tu, Y., Wei, J., Tang, S., Song, Y., and Fu, G., "Numerical Investigation on Thermal Performance Improvement of Hydrogen-fueled Tube with Rib/Fins for Micro Thermophotovoltaic." Applied Thermal Engineering, vol. 233, p. 121107, 2023.

[35] Zhao, S., Wei, Y., Yu, P., Nie, Y., Hu, R., He, W., Zhu, N., Li, Y., Ji, D., and Guo, K., "High Throughput Millifluidics Mixer with Double Triangle Baffle for Improvement of Mixing Performance and Reduction of Flow Resistance Designed by Grey Relational Analysis." Chemical Engineering and Processing - Process Intensification, vol. 181, p. 109166, 2022.

[36] Tang, X., Wan, W., Zhang, Z., Gao, W., and Wang, Y., "Residual Deformation of Coal Gangue Subgrade Filler under Multi-vibration Cyclic Loading." Scientific Reports, vol. 13, no. 1, pp. 1-15, 2023.

[37] Gao, F., Tian, L., Meng, F., Xia, Y., Shi, C., Zhang, Z., Cui, Y., Liu, S., and Li, J., "A Novel Dynamic Model and Simulations on Abnormal Wear of a Space Shaft Cage Worked at Low Temperature Environment." Tribology International, vol. 189, p. 108952, 2023.

[38] Tanürün H.E, “Improvement of vertical axis wind turbine performance by using the optimized adaptive flap by the Taguchi method.” Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, vol. 46. No. 1, pp. 71-90, 2023.

[39] Emziane, M., and Al Ali, M, “Performance assessment of rooftop PV systems in Abu Dhabi.” Energy and Buildings, vol. 108, pp. 101-105, 2015.

[40] Sharma, V., and Chandel, S. “Performance analysis of a 190 kWp grid interactive solar photovoltaic power plant in India.” Energy, vol. 55, pp. 476-485, 2013.

[41] Anang, N., Syd Nur Azman, S., Muda, W., Dagang, A., and Daud, M. Z, “Performance analysis of a grid-connected rooftop solar PV system in Kuala Terengganu, Malaysia.” Energy and Buildings, vol. 248, p.111182, 2021.

[42] Okello, D., Van Dyk, E., and Vorster, F. “Analysis of measured and simulated performance data of a 3.2 kWp grid-connected PV system in Port Elizabeth, South Africa.” Energy Conversion and Management, vol. 100, pp. 10-15, 2015.