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COMPARISON OF ADVANCED PV TECHNOLOGIES IN ALIAGA REGION: PERC AND TOPCON ANALYSIS

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JURY APPROVAL PAGE

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ABSTRACT

COMPARISON OF ADVANCED PV TECHNOLOGIES İN ALIAGA REGION: PERC AND TOPCON ANALYSIS

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Solar photovoltaic (PV) technologies have become a significant focus in the renewable energy sector due to the increasing global energy demand and the urgent need for sustainable energy solutions. This study compares the energy production performances of two advanced photovoltaic cell technologies, monocrystalline PERC (Passified Emitter and Back Cell) and TopCon (tunnel oxide passivated contact), under the same conditions in Aliağa Çoraklar, one of the regions with high solar energy potential in Turkey.

Comprehensive simulations performed with PVSyst software showed significant changes in terms of efficiency, temperature resistance and production costs. While TOPCon technology shows better performance due to its advanced structural design such as tunnel oxide layer, PERC technology is still attractive for cost-oriented applications. The study comprehensively analyzes the production capacities and sustainable energy impacts of these technologies, providing important information to decision makers and investors for the renewable energy sector. Furthermore, the role of innovative photovoltaic technologies in advancing Turkey's renewable energy targets is emphasized when considering energy storage integration and economic feasibility.

Keywords: Solar Energy , Photovoltaic Technologies ,TOPCon PV , PERC PV, Energy Efficiency ,Sustainable Energy, PVSyst

ÖZ

ALİAĞA BÖLGESINDE İLERİ PV TEKNOLOJİLERİNİN KARŞILAŞTIRILMASI: PERC VE TOPCON ANALİZİ

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Güneş fotovoltaik (PV) teknolojileri, artan küresel enerji talebi ve sürdürülebilir enerji çözümlerine acil ihtiyaç nedeniyle yenilenebilir enerji sektöründe önemli bir odak noktası haline gelmiştir. Bu çalışma, Türkiye'nin yüksek güneş enerjisi potansiyeline sahip bölgelerinden biri olan Aliağa Çoraklar'da aynı koşullar altında iki gelişmiş fotovoltaik hücre teknolojisinin monokristalin PERC (Pasifleştirilmiş Emitör ve Arka Hücre) ve TopCon (tünel oksit pasifleştirilmiş temas) enerji üretim performanslarını karşılaştırmaktadır.

PVSyst yazılımı ile gerçekleştirilen kapsamlı simülasyonlar, verimlilik, sıcaklık direnci ve üretim maliyetleri açısından önemli değişiklikler göstermiştir. TOPCon teknolojisi, tünel oksit tabakası gibi gelişmiş yapısal tasarımı nedeniyle daha iyi performans gösterirken, PERC teknolojisi maliyet odaklı uygulamalar için hala caziptir. Çalışma, bu teknolojilerin üretim kapasitelerini ve sürdürülebilir enerji etkilerini kapsamlı bir şekilde analiz ederek, yenilenebilir enerji sektörü için karar vericilere ve yatırımcılara önemli bilgiler sunmaktadır. Ayrıca, enerji depolama entegrasyonu ve ekonomik fizibilite dikkate alındığında, yenilikçi fotovoltaik teknolojilerinin Türkiye'nin yenilenebilir enerji hedeflerini ilerletmedeki rolü vurgulanmaktadır.

Anahtar kelimeler: Güneş Enerjisi, Fotovoltaik Teknolojileri, TopCon PV, PERC PV , Enerji Verimliliği, Sürdürülebilir Enerji,

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(This part will be blank in the submission of the thesis for the thesis defense. It will be added on the final submission.)

Merve Kansu
İzmir, 2025

TEXT OF OATH

I declare and honestly confirm that my study, titled "COMPARISON OF ADVANCED PV TECHNOLOGIES IN ALIAĞA REGION: PERC AND TOPCON ANALYSIS" and presented as a Master's Thesis, has been written without applying to any assistance inconsistent with scientific ethics and traditions. I declare, to the best of my knowledge and belief, that all content and ideas drawn directly or indirectly from external sources are indicated in the text and listed in the list of references.

Merve KANSU

May 2025

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SYMBOLS AND ABBREVIATIONS

SYMBOLS:

Si	Silicon
Cu2S / CDS	Copper(I) Sulfide / Cadmium Sulfide
Vmax	Maximum Voltage
Vmin	Minimum Voltage
Vmpp	Voltage at Maximum Power Point
Voc	Voltage at Open Circuit
Imax	Maximum Current
Imin	Minimum Current
Isc	Short-Circuit Current
Impp	Current at Maximum Power Point

ABBREVIATIONS:

AC	Alternating Current
DC	Direct Current
PV	Photovoltaic
TOPCon	Tunnel Oxide Passivated Contact
PERC	Passivated Emitter and Rear Cell
GENSED	Güneş Enerjisi Sanayicileri ve Endüstrisi Derneği
MINP	Metal Insulator n type / p type
PESC	Passive Emitter Solar Cells

LID	Light-induced Degradation
EROI	Carbon Emission and Lower Energy Return Ratio
CIGS	Copper Indium Gallium Selenide
HJT	Heterojunction Technology
CVD	Chemical Vapor Deposition
PECVD	Plasma-Enhanced Chemical Vapor Deposition
EVA	Ethylene Vinyl Acetate
EL	Electroluminescence
STC	Standard Test Conditions
LPCVD	Low-Pressure Chemical Vapor Deposition
APCVD	Atmospheric Pressure Chemical Vapor Deposition
LCOE	Levelized Cost of Electricity
ISE	Fraunhofer Institute for Solar Energy Systems
MPTT	Maximum Power Point Tracking
DOD	Depth Discharge Rate
PR	Performance Ratio
BMS	Battery Management System

1. CHAPTER: INTRODUCTION

Solar photovoltaic (PV) technology is vital for sustainable energy systems due to the increasing global energy demand and environmental threats. The transition from fossil fuels to renewable energy sources has become a necessity not only because of concerns about energy security but also because of the urgent need to reduce carbon emissions and combat climate change. Among various renewable energy sources, solar energy is one of the most preferred sources because it is more accessible and its electricity generation system is more basic and cost-effective.

Historically, the discovery of the photoelectric effect by Edmund Becquerel in 1839 [Becquerel, 1839] laid the foundation for modern solar energy technologies. However, practical applications of solar energy remained limited until the development of the first silicon solar cell by Daryl Chapin, Calvin Fuller and Gerald Pearson at Bell Labs in 1954 [Chapin et al., 1954]. While the efficiency of the first generation solar cells was about 7%, today's crystalline silicon-based solar cells have exceeded 25% efficiency in commercial applications. In addition, multi-junction solar cells have achieved efficiency of up to 43.5% under intense sunlight [Green et al., 2011], making them a promising option for high-performance energy applications. The continuous evolution of PV technology has been driven by both scientific developments and market dynamics. Over the last few decades, technological advances, manufacturing innovations, and economies of scale have significantly reduced the cost of solar panels. The experience curve model shows that the cost of PV technology decreases by approximately 20% for every doubling of manufacturing capacity [van Sark et al., 2008]. This cost reduction is a major factor in the widespread adoption of solar energy, making it more accessible to both large-scale utilities and small-scale residential applications.

The rapid expansion of the solar industry has been largely supported by government incentives and policy mechanisms. Many countries, including Germany, China, and the United States, have implemented feed-in tariff programs, tax incentives, and subsidies to encourage solar energy deployment. As a result, global solar energy

production has grown exponentially, with annual production growth rates exceeding 30% in the past decade [Kazmerski, 2012]. These policies have not only accelerated the adoption of PV technology, but have also encouraged research and development, leading to continuous improvements in efficiency and manufacturing processes. The falling equalized cost of electricity (LCOE) for solar energy has made it one of the most competitive renewable energy sources, surpassing even fossil fuel-based electricity generation in many regions.

In addition to its economic benefits, solar energy plays a fundamental role in achieving sustainability goals and mitigating climate change. The United Nations Brundtland Commission defined sustainability as "meeting the needs of today without compromising the ability of future generations to meet their own needs" [UNBC, 1987]. Sustainable energy sources, such as solar energy, contribute to global efforts such as the Paris Agreement and the Sustainable Development Goals (SDGs) by providing reliable, accessible, and environmentally friendly solutions [Khan and Sahabuddin, 2022]. Solar power's near-zero greenhouse gas (GHG) emissions significantly reduce the carbon footprint of electricity generation, making it a key driver of the global energy transition.

Apart from its advantages, there are also some challenges. For example, the widespread integration of solar energy into energy grids is highly dependent on external factors of the region where it will be installed. Variability in solar radiation due to weather conditions and seasonal changes affects energy output, necessitating the development of advanced energy storage systems and smart grid technologies. Innovations in battery storage, such as lithium-ion and solid-state batteries, and the integration of artificial intelligence into energy management are vital to optimizing the reliability and efficiency of solar energy systems. Additionally, material efficiency and end-of-life recycling of PV modules remain critical areas of research to increase the sustainability of solar technology. Addressing these challenges will be essential to ensure the long-term viability and expansion of PV technology as a cornerstone of the renewable energy landscape.

The increasing demand for clean and renewable energy solutions has led to a surge in large-scale solar projects worldwide, with many countries embarking on efforts to increase their solar capacity as part of their commitment to carbon neutrality. For example, Turkey has realized its high solar potential and is actively expanding its photovoltaic plants to diversify its energy mix and reduce its dependency on fossil fuel imports. By analyzing the comparative performance of different PV cell technologies under real-world conditions, this paper aims to provide valuable insights into the potential of solar energy as a sustainable and economically viable energy solution.

This study reveals several fundamental reasons for the selection of the Aliağa region. Initially, Aliağa has an important geographical location in the west of Turkey as an industrial and energy center close to İzmir. The solar energy potential of the region is quite advantageous. Aliağa and its surroundings receive more sunlight than the annual average sunshine duration of Turkey, providing high energy production efficiency. In addition, the region provides an excellent environment to evaluate the performance of photovoltaic systems, as it has mostly clear and sunny days throughout the year.

Aliağa has become a strategic focal point for evaluating the feasibility of photovoltaic technologies as a result of investments in industrial infrastructure and energy systems. However, the increasing energy demand of the region increases the need for renewable energy solutions and creates an opportunity to evaluate how photovoltaic technologies work in real field conditions.

1.1. Technological Differences

This thesis was found to compare the energy production performances of two different advanced photovoltaic (PV) cell technologies, monocrystalline PERC (Passivated Emitter and Rear Cell) and TOPCon (Tunnel Oxide Passivated Contact), and to draw conclusions from the results.

Perc cells, which are developed with a passivation layer applied to the back surface of traditional crystalline silicon solar cells, increase energy conversion efficiency by reducing electron loss on the surface. Being one of the most widely used PV technologies worldwide, it has low production costs and can be easily adapted to existing production lines. However, it also has some disadvantages. For example; It can experience performance loss in high temperature conditions and can be more sensitive to light-induced degradation (LID) effect.

TOPCon technology has an advanced cell structure containing tunnel oxide and polycrystalline silicon layers. This design minimizes electron loss with the passive contact effect and increases energy efficiency. In addition, it provides significant advantages in energy production due to its bifacial use against temperature changes. However, it also has disadvantages. For example, production processes are more complex than perc technology, and initial costs are higher. This slows down its spread and progress.

1.2. Purpose of Study

This study compares two advanced PV technologies—monocrystalline PERC and TOPCon—used in a 1 MW solar installation in the Aliağa region. By evaluating their energy production performance under the same conditions, it is aimed to reveal the efficiency differences of these technologies and their effects on sustainable electricity production. This analysis aims to provide important information that will guide decision makers and investors for the future applications of PV technologies. Initially, the historical development and fundamental features of PV technologies will be examined in detail

2. CHAPTER: PROBLEM DEFINITION

The increasing global energy demand and the necessity to reduce carbon emissions have made the transition to renewable energy sources an urgent priority. Among these sources, solar energy plays an important role due to its sustainability, easy applicability and technological advances. However, the efficiency, cost-effectiveness and long-term sustainability of photovoltaic (PV) technologies continue to be important research areas. Different PV technologies exhibit different performance levels in different climatic conditions, which reveals the need to compare the applied technologies to optimize solar energy production and to advance the appropriate and beneficial ones.

The most talked about and applied monocrystalline PERC (Passivated Emitter and Back Cell) and TOPCon (Tunnel Oxide Passivated Contact) solar cell technologies in the solar energy sector today are known as the leading solutions in the solar energy sector.

The Aliağa region in Turkey offers an ideal environment to evaluate the real-world performance of these PV technologies. With high solar radiation levels and increasing industrial energy demands, Aliağa offers a representative test site to evaluate the efficiency and applicability of PERC and TOPCon technologies. However, there is a significant gap in the literature regarding the comparative analysis of these two technologies under field conditions in this region. Addressing this gap, this study aims to analyze the energy production differences between PERC and TOPCon panels using simulation data obtained from PVSyst software. By simulating their performance under the same conditions, the research provides valuable information on their efficiency, durability, and integration potential into large-scale solar energy projects.

This study also explores the broader impact of choosing the right PV technology for sustainable energy. The findings aim to support data-driven decisions by investors, policymakers, and engineers in future solar projec

3. CHAPTER: LITERATURE REVIEW

The literature review is organized into four categories. The first research objective aims to analyze the root causes of container damage in the transportation process. The following topic explores studies on container damage estimation using machine learning models. firtsLastly, the review delves into the selection of appropriate machine learning models and methods to prevent overfitting. Since the correct model selection is important and overfitting is one of the main problems that can be encountered while working in the machine learning environment.

3.1. What is Solar Energy and Its Effects

Solar energy is a renewable energy source derived by converting the energy emitted as electromagnetic radiation, resulting from fusion reactions occurring in the sun's core, into a usable form. In this process, a large amount of energy is released during the transformation of hydrogen atoms into helium, which reaches the Earth's atmosphere as sunlight. Approximately 47.5% of the solar energy that reaches the atmosphere is transmitted to the Earth's surface and converted into heat. This energy possesses the potential to meet the planet's annual energy needs thousands of times over. Furthermore, solar radiation plays a crucial role in climate regulation, weather patterns, and ecological balance by influencing global temperature and atmospheric circulation.

The amount of solar energy reaching the Earth's surface varies depending on geographical location, weather conditions, and atmospheric factors. While the solar energy intensity measured outside the atmosphere is 1367 W/m², this value can drop to 1000 W/m² on the Earth's surface due to the atmosphere's effects, including absorption and scattering by clouds, dust, and gases. Solar energy is converted into electrical energy through photovoltaic (PV) systems, into thermal energy via thermal systems, and can also be utilized directly through passive methods such as solar heating and daylighting in architectural designs. These versatile applications make solar energy an ideal resource for a sustainable future, providing both environmental and economic benefits by reducing greenhouse gas emissions and dependency on fossil fuels (Koç, 2021).

3.1.1. Development and Future of Solar Energy Technology

Solar energy began to find its place in modern energy production with the development of solar panel technology by Daryl Chapin, Gerald Pearson, and Calvin Fuller at Bell Telephone Laboratories nearly 60 years ago. This groundbreaking invention found concrete application with the launch of the first solar-powered satellite, Vanguard, into orbit on March 17, 1958. Although solar panels were first used in space exploration, they now play a critical role in meeting global energy needs.

In 2010, the annual production of the photovoltaic (PV) industry exceeded 20 GW, and the sector reached an economic volume of approximately $70 billion by 2011. This rapid growth continued with an annual increase rate of over 30%, and the growth rate exceeded 100% in 2010. During this process, government incentives from Germany and Japan were one of the most important driving forces supporting the sector. Germany and Japan not only increased their market share, but also created high-value jobs and economic benefits. China, which quickly adapted to this model, became the leader in the sector by producing 50% of the world's PV products as of 2010. This rapid growth of PV technology was achieved not only by increasing production capacity, but also by lower system costs and improved material performance. As a result, solar energy is no longer a marginal technology in energy portfolios, but has become a real business line in the electricity sector.

3.1.2. The Evolution of Technology and the Importance of Disruptive Innovations

Today, crystalline silicon (Si) technologies, which dominate the PV market, are widely used to meet short-term needs. However, it is predicted that existing technologies may be insufficient to meet the increasing energy demands in 2020 and beyond. Therefore, innovative and so-called "disruptive technologies" solutions are needed. These technologies open new horizons that will provide market advantage by improving the cost-performance balance. Innovative materials like thin films will be vital for PV progress.

3.1.3. The Energy Source of the Future: Solar Energy

In recent years, the increase in energy demand and the environmental impacts of fossil fuels have increased the importance of renewable energy sources. Solar energy is one of the most striking among these sources with its unlimited, clean and environmentally friendly structure. The International Energy Agency (IEA) predicts that 11% of global electricity production will be provided by solar energy by 2050. In addition, while renewable energy capacity has increased threefold since 2000, solar capacity has increased 500-fold. (Kılıç , 2015) (Koç , 2021)

This impressive growth has been made possible by technological advances, decreasing costs, and government incentives. The increasing efficiency of solar energy indicates that this source will play a critical role in future energy production and will play an important role in sustainable energy solutions. The development of solar panels with evolutionary and disruptive technologies will continue to contribute to both economic growth and global energy security.

3.2. Solar Energy in Turkey

Turkey is an advantageous country in solar energy production due to its geographical location. With 2737 hours of annual sunshine and 1527 kWh/m² of annual energy potential, Turkey is in an ideal position to evaluate this resource. However, the current potential is not fully utilized. Government incentives and regulations are of critical importance for the widespread use of solar energy. Turkey has set a goal of increasing its installed solar energy capacity to 3000 MW by 2023. Solar energy projects are an effective tool for ensuring energy supply security, reducing external dependency and contributing to local economies. In addition, modernizing the energy infrastructure and implementing innovative technologies will allow Turkey to better evaluate its solar energy potential (Kılıç ,2015).

Solar energy has been a rapidly growing energy source worldwide and in Turkey since 2000. While the global solar energy installed capacity was around 1.5 gigawatts (GW) in 2000, this figure reached 710 GW by the end of 2020 (10.30784-epfad.890910-1…). As of 2023, the global solar energy installed capacity has increased to 1.6 terawatts (TW). This rapid increase shows that the share of solar energy in energy production is increasing (Solar Energy and Economic Growth.) A similar growth trend has been observed in Turkey. While the solar energy installed capacity was 7,816 MW in 2021, this figure reached 18,839 MW as of October 2024. These data show that Turkey's solar energy capacity has increased significantly in recent years and that investment in renewable energy sources has accelerated (Koç ,2021).

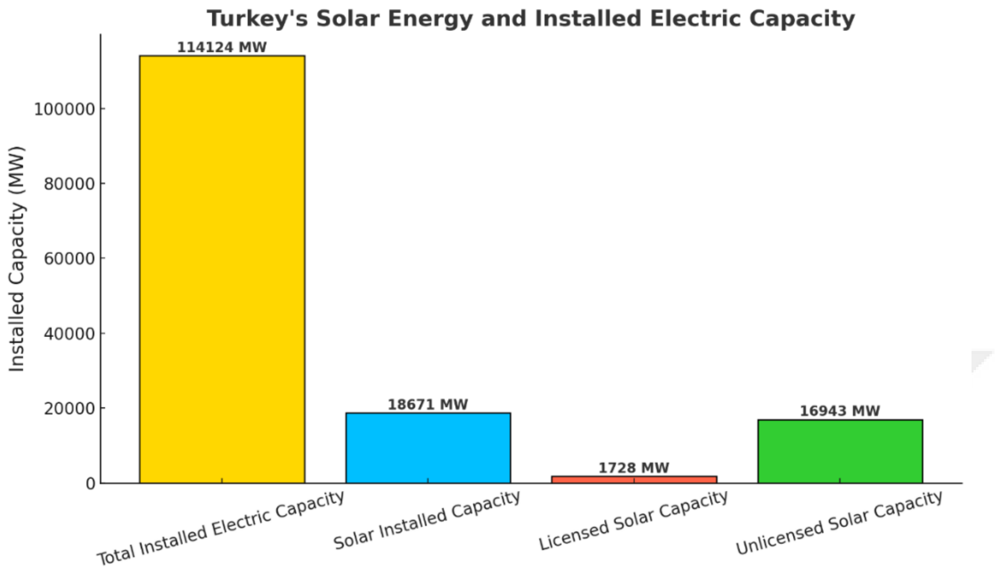


Figure 3.1. Turkey's Solar and Total Capactiy in 2024

Source: Solar Energy Industrialists and Industry Association (GENSED,2025).

3.2.1. Economic and Environmental Impacts

Solar energy attracts attention with its contributions to economic growth as well as its environmental benefits. In a study covering the years 1990-2019, it was determined that the use of solar energy is positively related to economic growth. This technology is an effective tool in combating climate change by reducing carbon emissions. At the same time, it reduces energy imports, increases energy supply security and supports economic development by creating local employment opportunities. Thanks to its environmentally friendly structure, solar energy reduces air pollution, protects water resources and helps protect natural ecosystems. With these features, solar energy is an ideal solution for both economic sustainability and environmental protection .

3.2.2. PV Technologies

➢ **Crystalline Silicon (Si) and Its Development Process**

The simple p-n junction designs of the 1980s have evolved into more complex and intelligent structures that aim to capture every photon, maximize electron-hole pair production, and optimize current generation by increasing the lifetime of these carriers. These developments include innovative designs such as metal/insulator/n-type/p-type (MINP), passive emitter solar cells (PESC), embedded contact cells (SSBC and DSBC), point contact and bidirectional cells.

Under laboratory conditions, Si cells have reached 90% of the theoretical limit by converting approximately one-fourth of the incident light photons into electrical energy.

➢ **Evolution of Silicon and Early Thin Film Technologies (AMOF, Nano, Micro, Polycrystalline)**

The Si industry is accelerating the achievement of market targets by strengthening material economics through methods such as the use of thinner wafers, reducing shear losses, adopting alternative thin Si production methods, reducing process costs, and improving performance. Today, solar cells with efficiency above 23% and modules with efficiency above 20% have been produced in commercial production lines.Thin-film technology is seen as a young but potentially powerful relative of crystalline Si.

In the mid-1970s, a new class of semiconductors emerged as an ideal candidate for PV. However, the physical structure of amorphous Si is completely different from crystalline Si. Defects caused by the "dangling bonds" of the amorphous structure have limited the efficiency of this material.

Thin-film PV has a long history; for example, Cu_2S/CdS devices were considered as the energy source for the Vanguard satellite.

Amorphous, nano, micro and polycrystalline thin films are notable for their cost advantages, flexibility and low-light operation, but they are still in the maturation phase. (Wevolver, n.d.)

➢ **N-Type Semiconductors: Electron Donors**

N-type semiconductors are materials with special electrical properties designed by adding certain impurities (dopants) to the crystal structure. These dopants, which usually come from Group V of the periodic table (e.g. phosphorus or arsenic), provide extra electrons to the material and significantly change its electrical properties.

They increase electrical conductivity by increasing the free electron density thanks to donor dopants. Electrons, which are negative charge carriers, facilitate current conduction, while the Fermi level approaches the conduction band and the energy levels in the band structure are filled. These properties provide higher conductivity compared to pure semiconductors. Phosphorus increases conductivity by providing an extra valence electron and has a solubility limit of approximately 1.5 × 10^21 atoms/cm³ at 1100°C. Arsenic, which is preferred in high-performance devices, offers high electron mobility and has a solubility limit of 1.7 × 10^21 atoms/cm³. Less commonly used antimony can create lattice strain due to its large atomic diameter and has a resolution limit of 7 × 10^20 atoms/cm³.

In recent years, N-type semiconductors have also been widely used in bifacial photovoltaic (PV) modules. With transparent back coating technology, light is allowed to pass through the back surface and produce energy on the second surface. These coatings have a light transmittance of over 80% and improve thermal performance thanks to their low density (Yu , 2016). In addition, the resistance of N-type silicon to light-induced degradation (LID) and its lesser effect from impurities increase energy production performance in the long term.

TOPCon (Tunnel Oxide Passivated Contact) technology is an innovative approach that increases the efficiency of N-type PV cells while minimizing energy losses. This technology provides passivation on the cell surface by creating an ultra-thin oxide layer and increases light absorption efficiency. In addition, cells manufactured with TOPCon technology use thin-cut wafer technology that reduces silicon consumption. This has significantly reduced silicon consumption in 182 mm N-type modules manufactured in 2023 (Wang et al., 2024).

- **P-Type Semiconductors: Hole Providers**

P-type semiconductors are one of the basic building blocks of electronic devices. In these semiconductors, which are created using dopants from Group III of the periodic table (e.g. boron, aluminum, gallium), a missing valence electron creates positive charge carriers called "holes". These holes provide current conduction as the primary positive charge carriers and move by borrowing electrons from neighboring atoms.

The hole density varies between 10^{15}–10^{20} cm^{-3} depending on temperature and dopant density, while the Fermi level approaches the valence band. The conductivity properties of P-type semiconductors are optimized with dopants that increase hole mobility. Boron is a widely used dopant in silicon, and aluminum provides broad doping control. Gallium is used in advanced technologies such as LEDs and laser diodes.

A study conducted in China analyzed the environmental impacts of P-type PV modules from production to recycling. The study indicated that P-type modules have higher carbon emissions and lower energy return ratio (EROI) compared to N-type PV modules. For example, 182 mm N-type modules produce 429.47 kgCO2eq emissions during their life cycle, while this value is higher in P-type modules (Wang ,2024).

P-type modules are preferred in small-scale and low-budget projects, especially due to their initial production costs. However, equipping N-type modules with innovative technologies such as TOPCon provides advantages over P-type modules by increasing energy production capacity and environmental sustainability.

- **Differences Between N-Type and P-Type Cells**

N-type and P-type photovoltaic cells show significant differences in terms of dopant materials used, electrical properties, environmental effects and long-term performance. The main differences between these two types of cells can be summarized as follows:

Charge Carriers: N-type cells use electrons (negative charge carriers) to conduct current. This provides the advantage of higher mobility and lower resistance.

P-type cells use holes (positive charge carriers). Hole mobility is lower than electrons, which generally leads to lower conductivity.

Additives: N-type cells are doped with donor dopants such as phosphorus, arsenic or antimony. These dopants increase conductivity by adding an extra electron to the crystal structure.

P-type cells are doped with acceptor dopants such as boron, aluminum or gallium. These dopants provide positive charge carriers by creating a missing electron ("hole") in the valence band.

Performance and Durability: N-type cells are resistant to light-induced degradation (LID) and are less affected by impurities. This increases long-term energy production performance.

P-type cells are more sensitive to the LID effect and the negative effects of impurities on performance are more pronounced.

Environmental Impact and Carbon Footprint: N-type cells have a lower carbon footprint thanks to innovative production techniques (e.g. TOPCon). In addition, the recycling rate of the materials used is higher.

P-type cells are less disadvantageous in terms of carbon emissions and their production processes can be energy intensive.

Cost and Application Areas: P-type cells are widely preferred due to their lower production costs and are frequently used in small-scale projects.

N-type cells, although more costly, offer long-term high performance and efficiency in commercial and industrial projects.

These differences suggest that N-type cells are particularly advantageous in projects that prioritize high performance and environmental sustainability goals. However, P-type cells are still widely preferred in many application areas due to their low cost. Optimizing the balance between these two technologies is critical for the future of the photovoltaic industry.

3.3. Types of Solar Panels

Solar energy technology aims to optimize power generation with different types of panels. Each type of panel is suitable for various projects with its own characteristics, efficiency level, cost and application advantages. These technologies are known in the market as monocrystalline, polycrystalline, thin film, TOPCon, heterojunction and double-sided panels. Each of these types plays an important role in energy production by offering solutions for specific needs.

Monocrystalline Panels : Monocrystalline panels produced from a single crystal of silicon are known for their smooth structure and dark colors. They have high efficiency and provide effective energy production even in limited areas. Despite their high cost, they are long-lasting and their performance is generally quite good.

Polycrystalline Panels : Polycrystalline panels made from the combination of multiple crystals of silicon attract attention with their more irregular structure and blue tones. Although they are lower in cost than monocrystalline panels, their efficiency is slightly lower. They are often preferred because they offer medium-level efficiency and affordable prices.

Thin Film Panels (Thin-Film): Thin film panels are produced from different materials such as silicon, cadmium telluride (CdTe) or copper indium gallium selenide (CIGS). These flexible and lightweight panels provide ease of installation. Although they are low-cost, their efficiency is generally lower and they require large areas. However, they can be advantageous on large surfaces.

TOPCon (Tunnel Oxide Passivated Contact) Panels : Monocrystal-based TOPCon panels provide high efficiency using passive contact technology. Thanks to the oxide layer, the performance on the cell surface increases. These panels are especially preferred in projects requiring high efficiency.

Heterojunction Panels (HJT - Heterojunction Technology) : Heterojunction panels, which consist of monocrystalline cells combined with thin amorphous silicon layers, provide very high efficiency and perform well at low temperatures. Despite their high cost, they are frequently used in projects requiring high performance.

Bifacial Panels : Bifacial panels can receive light from both their front and back surfaces, increasing throughput. They are typically produced with monocrystalline, TOPCon or HJT cells and can perform better on open areas or reflective surfaces. The bifacial panel is discussed in more detail in the following stages.

3.3.1. Importance and Advantages of Bifacial PV Cells

Bifacial PV (Photovoltaic) devices exhibit superior performance in energy production compared to traditional monofacial cells thanks to their ability to absorb light from both the front surface and the back surface. While monofacial cells collect only direct solar radiation from the front surface, bifacial cells increase total energy production by absorbing both direct radiation and light reflected from surfaces (albedo). This feature increases the efficiency and economic advantages of solar energy systems, while providing a more sustainable energy production model.

The history of bifacial technology dates back to the 1960s. During this period, research conducted by Cuevas and his team revealed that up to 50% increase in electricity production could be achieved by collecting albedo light reflected from surfaces. This study made a significant contribution to understanding the basic advantages of bifacial modules. Today, bifacial PV devices stand out with their advantages such as increasing energy density and reducing land use, especially in areas with high albedo values.

The glass-glass technology used in the structure of bifacial modules provides resistance to moisture and light-induced deterioration. The ability of these modules to withstand low operating temperatures and reduce parasitic absorption losses are other important factors that increase their technological performance. In addition, these devices, which offer energy generation from double surfaces, can provide long-term cost savings and rapid return on investment with the increase in energy from albedo.According to the International Technology Roadmap, bifacial PV technology is expected to reach a 15% share in the global market by 2024. According to estimates by the US Department of Energy, the costs of bifacial technology can drop to 1 USD/W. These features make bifacial PV modules not only efficient but also an economical option.

3.3.2. Structural Advantages of Bifacial PV Modules

One of the biggest differences in the design of bifacial PV modules is the use of an open metal grid structure instead of a completely closed metal coating on their back surfaces. This structure allows light reflections (albedo) from the back surface to be absorbed more effectively, optimizing total energy production. In contrast, monofacial cells usually have a flat metal backing and can only absorb light from the front surface. This limits the performance of monofacial cells compared to bifacial cells. The image below shows the structural differences between bifacial and monofacial cells. Bifacial cells on the left have a grid-like back contact structure to absorb light from both the front and back surfaces. Monofacial cells on the right have a flat back contact structure that allows light absorption only from the front surface.

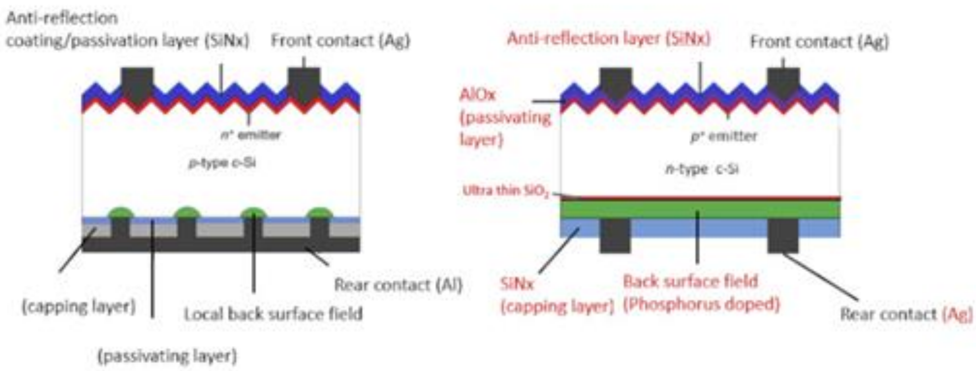


Figure 3.2 N Type and P Type Bifacial PV Panels of Differens

Source: TOPCon Solar Cells (Alternergy,2025).

3.3.3. The Role of Monocrystalline Panels and N-Type Cells

Monocrystalline panels, which are frequently used in bifacial panels, have a single silicon crystal structure, which provides high efficiency in energy production. N-type cells experience less loss in energy production due to electrons being the main carriers. They are also more resistant to light-induced degradation (LID) and are less affected by impurities. These features make N-type cells an ideal option for bifacial panels.

P-type cells, on the other hand, are more limited in terms of energy production due to the low mobility of hole carriers. Despite this, they are still preferred in some projects due to their low production costs and large-scale production advantages. However, the role of N-type cells used in bifacial panels in increasing total energy production is more evident.

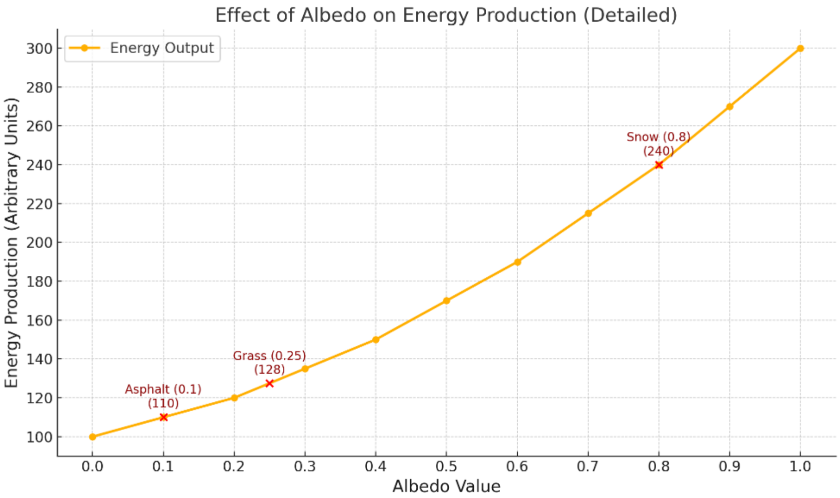
3.3.4. Simulation Studies and Performance Comparison

Simulation studies conducted to analyze the performance differences between bifacial and monofacial cells clearly reveal the superiority of bifacial cells. In the study conducted with SunSolve simulation software, the effect of albedo ratio on energy production was examined in detail. The graph below shows the contribution of different albedo values to energy production.

3.3.5. Electrical Parameters and Effect of Albedo

Simulation results show that bifacial cells perform better than monofacial cells in electrical parameters such as short circuit current (Jsc), open circuit voltage (Voc) and power production. With increasing albedo value, the back surface light absorption increases, which directly affects the total energy production. When installed on surfaces with high albedo (snow, water, concrete), bifacial modules become a superior option in terms of both economics and energy efficiency.

Table 3.1. Energy Production vs. Surface Albedo (Snow, Grass, Asphalt)



Source: Author

3.3.6. Future Potential of Bifacial PV Technology

Bifacial PV technology offers significant performance advantages over monofacial cells by providing energy production from both the front and back surfaces. This technology provides higher energy production and efficiency in areas with high albedo values. With the use of monocrystalline N-type cells, the performance of bifacial panels is further increased and these panels stand out among sustainable energy solutions. Further research on cell design, simulation accuracy and installation optimization for wider adoption of the technology will increase the future potential of bifacial PV modules.

3.4. Monocrystalline Panel Manufacturing Process

Before going into the details of the TOPCon panel, in order to understand the differences in production, the production of PV panels, which is common in the classical sector, will be discussed first.

Raw Material Preparation: High purity silicon is produced by Czochralski or float-zone methods and cut into thin slices. Czochralski and Float-Zone Methods: While the Czochralski method creates monocrystalline silicon by pulling a seed crystal from molten silicon, the Float-Zone method aims to melt a certain area of a silicon rod and push impurities to produce high purity crystals. Cut silicons are called wafers. Wafer surfaces are cleaned to remove impurities and a texture process is applied to the surface to better absorb light.

Oxide Layer Formation: A very thin oxide layer of 1-2 nm thickness is thermally formed on the wafer surface. This layer provides electron tunneling and minimizes recombination losses.

Polycrystalline Silicon Coating: A thin layer of polycrystalline silicon is coated on the wafer surface using chemical vapor deposition (CVD) or plasma-enhanced CVD (PECVD) methods. This layer acts as a passivated contact, allowing charge carriers to be collected more efficiently.

Doping and Diffusion: N-Type or P-Type Doping: The poly-Si layer is doped with phosphorus (n-type) or boron (p-type). This process is done to provide the desired electrical properties.

Anti-Reflective Coating: An anti-reflective coating is applied to the wafer surface to increase light absorption and reduce energy losses.

Metallization: Metallic contacts are applied to the wafer surface using screen printing or photolithography methods. The poly-Si layer provides low-resistance connections between silicon and the metallic contacts.

Passivation: Additional dielectric layers are applied to further reduce surface reconnection losses.

Assembly and Lamination: After passivation, the cells come to the panel production area. At this stage, the cells are first processed by the cutting machine and divided into halves. This cutting process is done with lasers in most factories, but this can cause loss of efficiency in the cell and cell burns. Therefore, cell cutting processes are done with water jet, so that burns do not occur in cells cut with water.

The cut cells are taken to the stringer (array) machine and here they are soldered with wires called ribbons and made into a series of six. The ribbon is a copper-plated wire. These wires are placed so that they pass under and over the cell while being soldered. Thus, + and - poles are formed. The prepared stringers are placed on the glass surface after being checked by eye and computer. Thus, individual solar cells are brought together to form a module. The module is encapsulated with materials such as EVA (ethylene vinyl acetate) and laminated between the glass and a backing sheet. In fact, Eva material is placed first on the glass surface, then cells in series are placed. Another EVA is placed on the placed cells and sent to lamination, where all the components come together. The function of EVA is to protect the cells, provide insulation and ensure that the panel components are integrated with each other. Once the panel that emerges from the lamination process has successfully passed the visual checks, the J boxes, which are responsible for providing the power output of the panel, are soldered in place, and the frames are subsequently attached.

Testing and Quality Control: Electroluminescence (EL) Test: Tests are performed to detect defects such as micro cracks or electrical inconsistencies. Performance Test: I-V curve tests are performed under Standard Test Conditions (STC) and electrical performance is verified.

Packaging and Shipping: Final Control: Each module undergoes final quality control and is then packaged and shipped to customers.

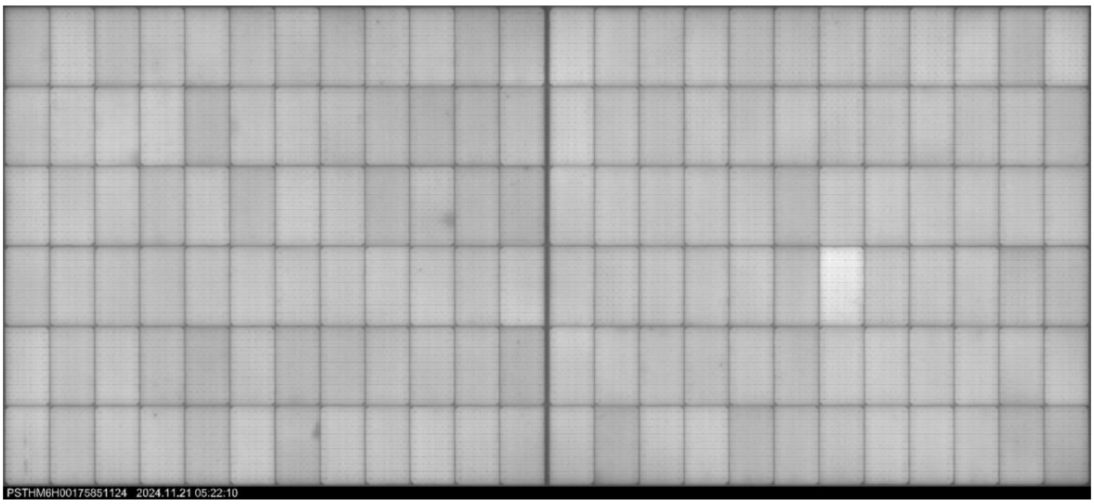


Figure 3.3. PV EL Test Report

Source: Author

	Paket No	Palet Sıra No	Seri numarası	Pm(W)	Isc(A)	Voc(V)	Ipm(A)	Vpm(V)	FF
2	PSTH-GC2-M6/24-42-653	1	PSTHM6H56665741024	553,309767	13,790000	50,220000	13,218705	41,858091	79,896428
3	PSTH-GC2-M6/24-42-653	2	PSTHM6H57865741024	554,119771	13,864729	50,526064	13,249229	41,822793	79,100054
4	PSTH-GC2-M6/24-42-653	3	PSTHM6H58165741024	553,150999	13,854208	50,626981	13,197378	41,913704	78,864211
5	PSTH-GC2-M6/24-42-653	4	PSTHM6H61175741024	554,105773	13,831239	50,619151	13,227938	41,889051	79,143768

Figure 3.4. FTR Report Panel Tests under Simulated Ratiation

Source: Author

STC (1000 W/m², AM 1.5, 25°C) test results are shown in Figure 3.4.2. Though TOPCon involves extra processing, it improves efficiency and durability for high-performance applications.

3.5. TOPCon PV Panel Technology

TOPCon (Tunnel Oxide Passivated Contact) is an advanced PV technology that improves efficiency by reducing recombination losses compared to conventional PERC cells. Its structure combines a polysilicon contact with a thin tunnel oxide layer, enhancing charge carrier selectivity and minimizing energy loss (Yousuf et al., 2021; Gebhardt et al., 2024). Laboratory and commercial implementations have reached conversion efficiencies up to 26% (Guenounou et al., 2016). Beyond technical performance, (Kafle et al.,2021) demonstrated its industrial feasibility through cost-effective manufacturing routes. Their findings underline TOPCon's growing potential to become a mainstream solution in photovoltaic production.

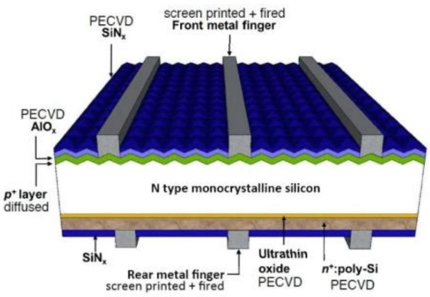


Fıgure 3.5. TOPCon PV Panel Structure

Source: N-Type Bifacil TOPCon Solar Cells (DS New Energy,2025)

3.5.1. Manufacturing Processes and Technological Structure

The production of TOPCon cells can be achieved by optimizing existing PERC production lines. In this process, several additional process steps are added to PERC cells. As a first step, a tunnel oxide layer is added. This layer is an ultra-thin oxide layer applied to the silicon surface, which allows the passage of carriers while preventing recombination. The tunnel oxide layer is formed on the silicon surface with a thickness of approximately 1-2 nm, thus minimizing minority carrier recombination. Subsequently, a polysilicon layer is created. Its high doping level improves electric conductivity and reduces losses. The polysilicon layer increases the current carrying capacity with low resistance, minimizing energy losses during metallization. These two layers significantly increase the performance of the solar cell. In addition, it provides surface passivation. (Yousuf et al., 2021). The next process is that the amorphous structure of the cell is transformed into a crystal structure by exposing the polysilicon layer to high temperature (high temperature annealing). Then, this crystal structure is subjected to metallization process and silver (Ag) contacts are formed on it to provide electrical connection. The biggest effect of using silver here is that it has high conductivity and low resistance compared to other metals such as copper. (Kumar et al., 2019), "Material properties and their impact on solar cell efficiency"). In addition, silver is quite durable outdoor conditions.

There are several industrial production methods used in TOPCon production. These methods are listed as follows.

3.5.1.1 LPCVD (Low-Pressure Chemical Vapor Deposition):

Process: Formation of tunnel oxide and phosphorus-doped polysilicon layers by chemical vapor deposition under low pressure.

Advantages:

- Provides high quality and homogeneous coating,
- Protects wafer purity with deposition at low temperatures (<600°C),
- Allows simultaneous processing of many wafers.

Disadvantages:

- Long process time and high equipment costs can increase production costs.

3.5.1.2 PECVD (Plasma-Enhanced Chemical Vapor Deposition):

Coating of polysilicon and tunnel oxide layers using plasma.

Advantages:

- It has faster deposition rates and lower process temperatures.

Disadvantages:

- Coating homogeneity may be lower than LPCVD.

3.5.1.3 APCVD (Atmospheric Pressure Chemical Vapor Deposition):

Coating by chemical vapor deposition method at atmospheric pressure.

Advantages:

- Production speed is high and costs are low.

Disadvantages:

- It may be difficult to achieve homogeneity in coating quality.

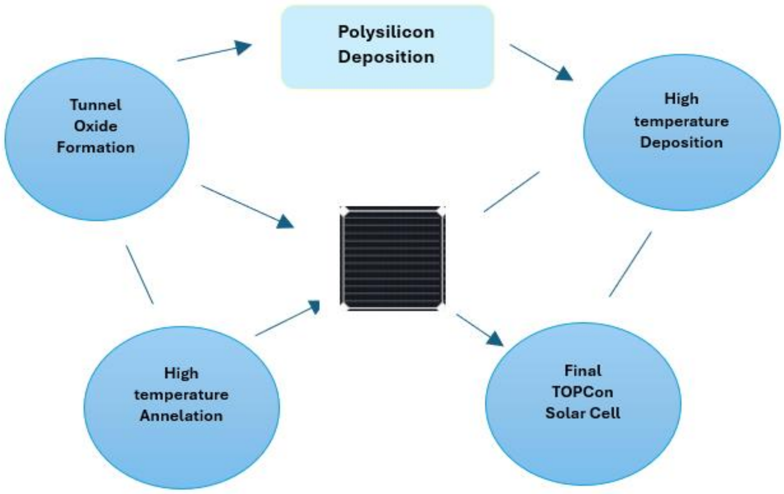


Figure 3.6. Flow Chart Summarizing the Production Process of TOPCon Solar Cells

Source: Author.

In summary, LPCVD, PECVD and APCVD processes that can be used during polysilicon coating in the above-mentioned steps have been optimized to be integrated into existing PERC production lines with minimum additional cost. However, additional steps, especially boron-doped donor diffusion, have not yet fully reached industrial maturity.

3.5.2. Efficiency and Performance

TOPCon technology provides significant efficiency increases in solar cells, both on laboratory and commercial scales.In laboratory studies, TOPCon cells have achieved conversion efficiencies exceeding 26%. In experiments conducted by Fraunhofer ISE, open circuit voltages (VOCs) of up to 725 mV were achieved. These results show that TOPCon cells demonstrate their energy conversion potential by significantly reducing recombination losses (Yousuf et al.,2021).

In industrial areas (during actual production), the conversion efficiency of TOPCon cells produced has reached up to 23.6%. This efficiency can be further increased in bifacial cell structures. (TOPCon – Technology options for cost efficient industrial manufacturing). When we look at their areas of use, the performance of bifacial panels with double faces provides higher energy output compared to standard PERC cells. This provides an economic advantage by reducing the LCOE (Levelized Cost of Electricity) value in large-scale installations (Guenounou, et al., 2016).

In tests conducted in field GES project installations, TOPCon modules have shown stable performance against temperature and light intensity changes. These test results may also vary regionally. For example, in studies conducted in the Mediterranean climate, it was observed that TOPCon modules were minimally affected by seasonal changes.

3.5.3. Performance Losses

In the production of TOPCon cells, optical, recombination and resistance-related losses have been minimized. In optical losses, light absorption has been increased thanks to anti-reflection coatings and a thin tunnel oxide layer. In losses occurring during recombination, tunnel oxide and polysilicon layer aim to minimize energy loss by increasing the lifespan of the carriers. In resistance losses, electrical losses have been reduced thanks to low contact resistance and optimized polysilicon layer structures. These improvements significantly increase the performance of TOPCon cells, making them a competitive solution compared to other technologies.

3.5.4. Advantages of TOPCon PV

The main advantages provided by TOPCon technology are as follows:

High Efficiency: Increases energy production capacity with conversion efficiencies reaching up to 26%. These values, which are over 26% in laboratory environments and up to 23.6% in commercial production, reveal the efficiency potential of the technology.
Recombination Reduction: Tunnel oxide and polysilicon layers greatly reduce recombination losses thanks to their carrier selective properties (Thome et al.,2024).
Low Production Cost: The ability to upgrade existing PERC production lines for TOPCon production at minimum cost provides cost advantage on an industrial scale.
Bifacial Performance: Thanks to the double-sided (bifacial) cell structure, TOPCon modules provide additional gains in energy production by also using the light reflected from the back surface. This offers significant advantages especially in large-scale PV plants.
Low Temperature Coefficient: The temperature performance of TOPCon cells is quite good. It keeps energy losses to a minimum even in high temperature conditions, which increases its efficiency in hot regions
Long-Life Performance: TOPCon cells are highly resistant to external factors such as UV radiation, humidity and temperature. Thus, long-term performance losses are less.
Low LCOE: In terms of Levelized Cost of Electricity, TOPCon technology offers a cost-effective solution in energy production.
Environmental Impact: High efficiency and long life reduce the carbon footprint of TOPCon modules. In addition, since the energy payback time is shorter, it is also advantageous in terms of environmental sustainability.

Thanks to these advantages, it is expected that this technology will become an important standard in the PV industry in the coming years.

3.5.5. Disadvantages of TOPCon PV

High Production Costs: The n-type silicon substrates used in the production of TOPCon cells are more costly than p-type substrates.

Additional process steps: such as tunnel oxide coating, polysilicon deposition, and high-temperature annealing increase production costs.

Equipment and Process Investment Requirement: Additional equipment investments and process developments are required to convert existing PERC production lines to TOPCon production. This can be a major financial burden, especially for small-scale producers.

Technical Complexity: The homogeneity of the polysilicon layer and the thinness tolerance of the tunnel oxide layer require precise control during production. This complicates production processes and affects production efficiency.

Efficiency Gain and Cost Balance: In order for TOPCon technology to be economically competitive, the conversion efficiency must exceed a certain level. This may create uncertainties in the cost-performance analysis compared to existing PERC cells.

High Temperature Sensitivity: The need for high temperatures in the production processes increases energy consumption and may increase the environmental impact of the production process.

Boron Diffusion Challenges: The integration of boron-doped emitters into production processes has not yet been fully optimized on an industrial scale.

Performance in Accelerated Aging Tests: Performance losses have been observed in some TOPCon modules in accelerated aging tests, particularly due to humidity and UV radiation. This requires further development of encapsulation materials and production methods (Gebhardt et al., 2024)

4. CHAPTER: PV CALCULATION

A comprehensive understanding of the calculations for proper inverter and panel matching in a 1 MW photovoltaic system is essential before progressing to the simulation phase. Ensuring appropriate matching is crucial and requires careful consideration of various factors to achieve optimum performance and efficiency. The configuration of panels, arrays, and inverters plays a significant role in maximizing energy production while minimizing costs and technical constraints. This analysis focuses on determining the proper panel-array configuration and inverter sizing, considering both minimum and maximum operating limits. In these calculations, the appropriate number of inverters, the number of panels in an array, and MPPT numbers are analyzed. Additionally, the most suitable number of batteries for integration into the system is determined. Consideration of temperature coefficients and module degradation rates is also necessary to ensure long-term system stability. Furthermore, three different PVs were utilized in the 1 MW photovoltaic system design planned for installation in the Aliağa region to evaluate production differences. These include 560W MonoPERC, 565W TOPCon (TOPCon production starts from 565W), and 690W TOPCon PV panels. The Huawei 110kW SUN2000-110KTL-M0 model was selected as the inverter, allowing for a comparative analysis of different PV technologies under real-world conditions, offering insights into efficiency variations.

The presence of an MPPT in an inverter significantly increases the performance of a 1 MW system. MPP Tracker (MPPT) is a feature in inverters that allows connected photovoltaic (PV) panels to operate at their maximum power point (MPP). MPP is the optimum combination of voltage (Vmpp) and current (Impp) at which the panel produces its highest power output under specific environmental conditions (such as sunlight intensity and temperature). Each MPPT independently optimizes the panel output to provide maximum energy harvest, even under changing conditions such as shading or temperature changes, thus minimizing energy loss. This feature is particularly useful in large-scale solar farms, where partial shading or uneven irradiance may affect different sections of the array. MPPTs increase system scalability by enabling large 1 MW designs to be subdivided into manageable subsections, ensuring efficiency across different panel orientations, tilt angles and environmental conditions, and allowing power outputs to be monitored and optimized.

4.1. Calculated for 560W MonoPERC PV

As an initial step, the number of panels and inverters in the 1 MW photovoltaic system is examined. The formulas 4.1.1, 4.1.6, 4.1.8, 4.1.14, and 4.1.17 are based on the IEEE 1562 standard (Institute of Electrical and Electronics Engineers, 2007). The formulas 4.1.3, 4.1.10, 4.1.19, 4.1.24, and 4.1.25 are calculated according to the IEC 61853-1 standard (International Electrotechnical Commission, 2018).

4.1.1. Number of Panels Calculation

$$N_p = \frac{P_{total}}{P_{panel}} \quad (1)$$

- N_p : Total number of panels
- P_{total} : Total system power (W)
- P_{panel} : Power of one panel (W)

Calculation:

$$N_p = \frac{1.000.000}{560} = 1786 \quad (2)$$

Approximately 1786 panels are required.

4.1.2. Maximum Panels per String

$$N_{string} \frac{V_{max}}{V_{oc}} \quad (3)$$

- N_{string} : Maximum number of panels in a string
- V_{max} : Maximum input voltage of the inverter (V)
- V_{oc} : Open circuit voltage of the 560W panel (Voc)

Calculation:

$$V_{oc} = 49.79 \quad (4)$$

$$N_{string} = \frac{1100}{49{,}79} = 22.1 \quad (5)$$

To ensure safety, we round down to 22 panels per string.

4.1.3. Total Number of Strings

$$N_{total_{string}} = \frac{N_p}{N_{string}} \quad (6)$$

$$N_{total_{string}} = \frac{1786}{22} = 81{,}18 \quad (7)$$

Approximately 82 strings are needed.

4.1.4. Strings per MPPT

$$N_{MPPT} = \frac{N_{total_{string}}}{M} \quad (8)$$

- N_{MPPT} : Number of strings per MPPT
- M : Number of MPPTs in the inverter

Calculation:

$$N_{MPPT} = \frac{82}{10} = 8{,}2 \quad (9)$$

Exactly 8 strings per MPPT. (Minimum string)

4.1.5. MPPT Input Current

$$I_{MPPT} = N_{MPPT} \; X \; I_{mpp} \quad (10)$$

- I_{MPPT} : Input current per MPPT (A)
- I_{mpp} : Operating current of one 560W panel (A)

Calculation:

$$I_{mpp} = 13.42\ A \quad (11)$$

$$I_{MPPT\_min} = 8\ X\ 13{,}42 = 107.39\ A \quad (12)$$

$$I_{MPPT\_max} = 10\ X\ 13{,}42 = 134.2\ A \quad (13)$$

This still exceeds the inverter's maximum input current per MPPT (30A), requiring adjustment of the string distribution.

4.1.6. Minimum Number of Panels per String

The minimum number of panels per string is determined by the MPP (Maximum Power Point) voltage range of the inverter.

Formula:

$$N_{min_{string}} = \frac{V_{min}}{V_{mpp}} \quad (14)$$

- $N_{min_{string}}$: Minimum number of panels per string
- V_{min} : Minimum MPP voltage of the inverter (200V from datasheet)
- V_{mpp} : Operating voltage of one panel at MPP (41.73V for 560W panel)

Calculation:

$$N_{min_{string}} = \frac{200}{41.73} \sim 4.79 \quad (15)$$

Rounding up, the minimum number of panels per string is *5*.

4.1.7. Minimum Number of Strings (Based on Inverter MPPT Limits)

The inverter has 10 MPPTs, with each MPPT capable of handling multiple strings. To ensure proper utilization, at least one string must be connected to each MPPT.Thus, the minimum number of strings required is

$$N_{min_{string}} = M = 10 \quad (16)$$

4.1.8. Minimum Number of Inverters

Now, let's calculate the minimum number of inverters required to achieve the total system capacity of 1 MW.

Formula:
$$N_{min_{inv}} = \frac{P_{total}}{P_{inv\_max}} \quad (17)$$

$P_{\min\_max}$: Maximum output power of one inverter

Calculation:
$$N_{min_{inv}} = \frac{1000}{121} \sim 8.2626 \quad (18)$$

Rounding up, the minimum number of inverters required is *8*.

Summary for Minimum Configuration:

1. Minimum panels per string: 5
2. Maximum panels per string: 22
3. Minimum strings (to utilize MPPTs): 10
4. Minimum inverters required: 8

Even in a minimal configuration, **at least 8 inverters** are needed to achieve the 1 MW target due to the inverter's maximum output limitations. As understood from the summary above, for the 560W MonoPERC panel, this simulation will proceed with 18 panels and 8 inverters per string. The reason for proceeding with these numbers is to comply with the appropriate ranges in the previous calculations and to simplify the design. The calculations showing the appropriateness of these numbers are as follows.

4.1.9. Total Panel Count

$$N_p = 18xN_{strings} \quad (19)$$

We need to determine how many strings are required to reach 1 MW.

4.1.10. Total System Power Calculation

$$P_{string} = 18x560 = 10{,}080W \ (10.08\ kW) \quad (20)$$

To reach 1 MW :

$$N_{strings} = \frac{1{,}000{,}000}{10{,}080} = 99{,}2 \tag{21}$$

Approximately 100 strings are required.

4.1.11. Strings per Inverter

$$N_{strings_{per_{inv}}} = \frac{100}{8} = 12.5 \tag{22}$$

Each inverter has 10 MPPTs. If we distribute 12 strings:

$$N_{MPPT} = \frac{12}{10} = 1.2 \tag{23}$$

Thus, about 1 or 2 strings per MPPT. This ensures each MPPT operates within optimal voltage and current limit.

4.1.12. Voltage and Current Check

String Voltage (Vmpp and Voc)

$$V_{strings_{mpp}} = 18\ X\ 41.73 = 751.14V \tag{24}$$

$$V_{string_{oc}} = 18\ X\ 49.79 = 896.22V \tag{25}$$

- This falls within the inverter's MPPT range (200-1000V).
- The open-circuit voltage (Voc) is below the inverter's maximum input voltage (1100V).

String Current (Impp and Isc):

$$I_{string_{mpp}} = 13{,}42\ A \tag{26}$$

$$I_{strings_{sc}} = 14{,}02\ A \tag{27}$$

Each MPPT can handle up to 30A per input, meaning two strings in parallel per MPPT is safe.

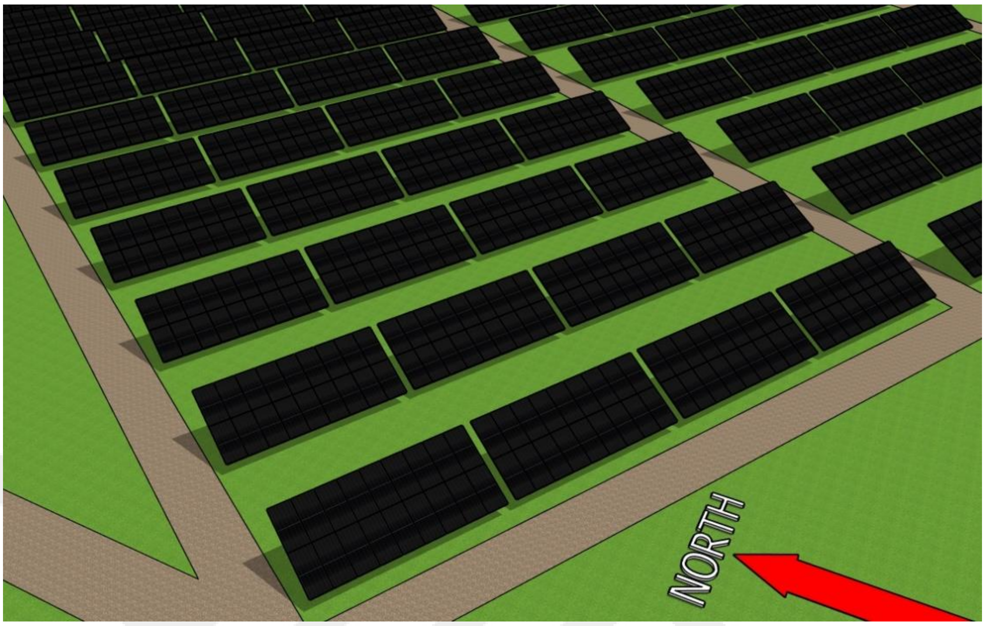


Figure 4.1. Layout of the 560W Monofacial PERC Panel System

Source: Author

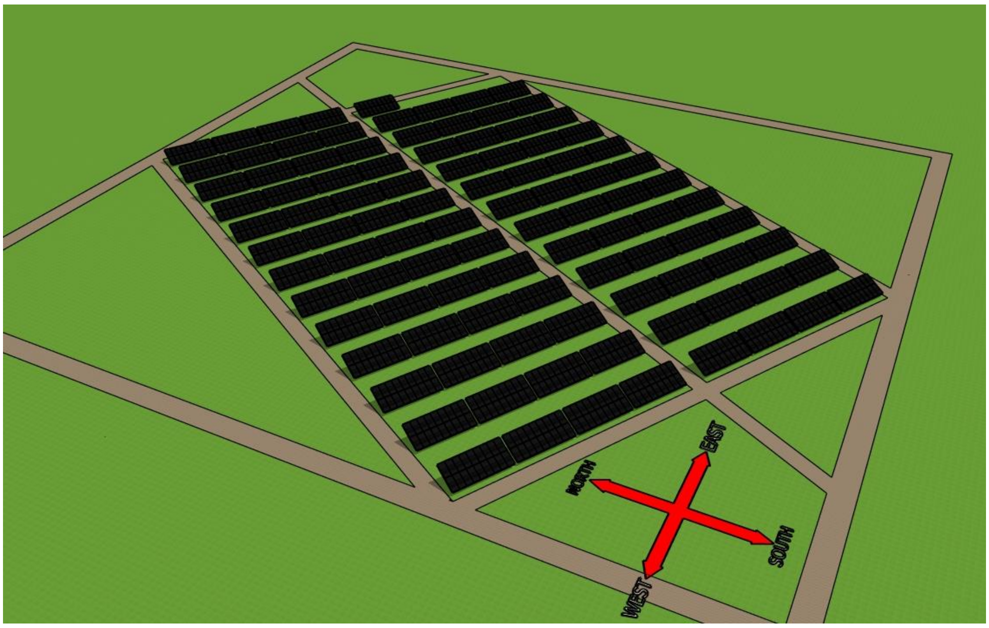


Figure 4.2. 3D Model of the 560W Monofacial PERC Panel Design

Source: Author

4.2. Calculated for 565W TOPCon

Subsequently, the number of panels and inverters in the 1.018 MW photovoltaic system is analyzed. The formulas 4.2.1, 4.2.6, 4.2.8, 4.2.14, and 4.2.17 are based on the IEEE 1562 standard (Institute of Electrical and Electronics Engineers, 2007). The formulas 4.2.3, 4.2.10, 4.2.19, 4.2.24, and 4.2.25 are calculated according to the IEC 61853-1 standard (International Electrotechnical Commission, 2018).

4.2.1. Number of Panels Calculation

$$N_p = \frac{P_{total}}{P_{panel}} \tag{28}$$

- N_p : Total number of panels
- P_{total} : Total system power (W)
- P_{panel} : Power of one panel (W)

Calculation:

$$N_p = \frac{1.018.130}{565} = 1802 \tag{29}$$

Approximately 1769 panels are required.

4.2.2. Maximum Panels per String

$$N_{string} = \frac{V_{max}}{V_{oc}} \tag{30}$$

- $\boldsymbol{N_{string}}$: Maximum number of panels in a string
- V_{max} : Maximum input voltage of the inverter (V)
- V_{oc} : Open circuit voltage of the 565W panel (Voc)

Calculation:

$$V_{oc} = 51.49 \tag{31}$$

$$N_{string} = \frac{1100}{51,49} = 21.36 \tag{32}$$

To ensure safety, we round down to 21 panels per string.

4.2.3. Total Number of Strings

$$N_{total_{string}} = \frac{N_p}{N_{string}} \tag{33}$$

$$N_{total_{string}} = \frac{1769}{21} = 84{,}23 \tag{34}$$

Approximately 84 strings are needed.

4.2.4. Strings per MPPT

$$N_{MPPT} = \frac{N_{total_{string}}}{M} \tag{35}$$

- N_{MPPT} **:** Number of strings per MPPT
- M : Number of MPPTs in the inverter

Calculation:

$$N_{MPPT} = \frac{84}{10} = 8{,}4 \tag{36}$$

Exactly *8 strings* per MPPT. (Minimum string)

4.2.5. MPPT Input Current

$$I_{MPPT} = N_{MPPT}\ X\ I_{mpp} \tag{37}$$

- I_{MPPT} : Input current per MPPT (A)
- I_{mpp} : Operating current of one 565W panel (A)

Calculation:

$$I_{mpp} = 13.24\ A \tag{38}$$

$$I_{MPPT\_min} = 8\ X\ 13{,}24 = 105.92\ A \tag{39}$$

$$I_{MPPT\_max} = 10\ X\ 13{,}24 = 132.4\ A \tag{40}$$

This still exceeds the inverter's maximum input current per MPPT (30A), requiring adjustment of the string distribution.

4.2.6. Minimum Number of Panels per String

The minimum number of panels per string is determined by the MPP (Maximum Power Point) voltage range of the inverter.

Formula:

$$N_{min_{string}} = \frac{V_{min}}{V_{mpp}} \tag{41}$$

- $N_{min_{string}}$: Minimum number of panels per string
- V_{min} : Minimum MPP voltage of the inverter (200V from datasheet)
- V_{mpp} : Operating voltage of one panel at MPP (42.68V for 565W panel)

Calculation:

$$N_{min_{string}} = \frac{200}{42.68} \sim 4.68 \tag{42}$$

Rounding up, the minimum number of panels per string is *5*.

Summary for Minimum Configuration:

- Minimum panels per string: 5
- Maximum panels per string: 21
- Minimum strings (to utilize MPPTs): 10
- Minimum inverters required: 8

Even in a minimal configuration, at least 8 inverters are needed to reach the 1 MW target due to the maximum output limitations of the inverter. Same for a 560W PV panel. As can be seen from the summary above, for a 565W MonoPERC panel this simulation would continue with 17 panels and 8 inverters per array.

4.2.7. Total Panel Count

$$N_p = 17xN_{strings} \quad (43)$$

We need to determine how many strings are required to reach 1 MW.

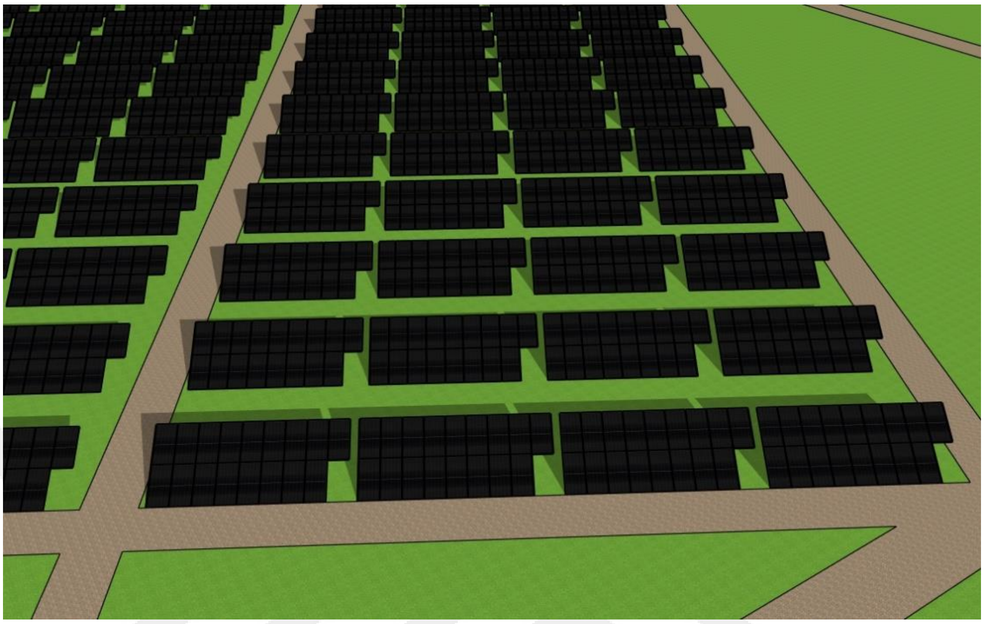


Figure 4.3. Layout of the Bifacial 565W TOPCon Panel System.

Source: Author

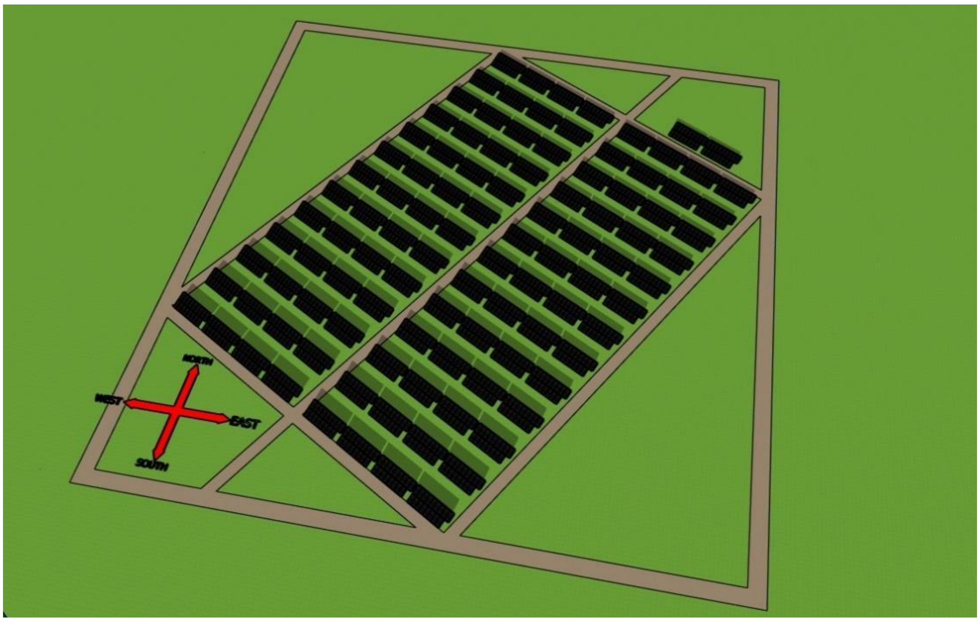


Figure 4.4. 3D Model of the Bifacial 565W TOPCon Panel Design

Source: Author

4.2.8. Total System Power Calculation

$$P_{string} = 17x565 = 9{,}605W\ (9.60\ kW) \quad (44)$$

To reach 1 MW:

$$N_{strings} = \frac{1{,}000{,}000}{9{,}605} = 104{,}112 \quad (45)$$

Approximately 104 strings are required.

4.2.9. Strings per Inverter

$$N_{strings_{per_{inv}}} = \frac{104}{8} = 13 \quad (46)$$

Each inverter has 10 MPPTs. If we distribute 13 strings:

$$N_{MPPT} = \frac{13}{10} = 1.3 \quad (47)$$

Thus, about 1 or 2 strings per MPPT. This ensures each MPPT operates within optimal voltage and current limit.

4.2.10. Voltage and Current Check

String Voltage (Vmpp and Voc)

$$V_{strings_{mpp}} = 17\ X\ 42.68 = 725.56V \quad (48)$$

$$V_{string_{oc}} = 17\ X\ 51.49 = 875.33V \quad (49)$$

- This falls within the inverter’s MPPT range (200-1000V).
- The open-circuit voltage (Voc) is below the inverter's maximum input voltage (1100V).

String Current (Impp and Isc):

$$I_{string_{mpp}} = 13{,}24A \quad (50)$$

$$I_{strings_{sc}} = 13{,}89\ A \quad (51)$$

Each MPPT can handle up to 30A per input, meaning two strings in parallel per MPPT is safe.

4.3. Calculated for 690W TOPCon

In the final step, the number of panels and inverters in the 1.049 MW photovoltaic system is analyzed."The formulas 4.3.1, 4.3.6, 4.3.8, 4.3.14, and 4.3.17 are based on the IEEE 1562 standard (Institute of Electrical and Electronics Engineers, 2007). The formulas 4.3.3, 4.3.10, 4.3.19, 4.3.24, and 4.3.25 are calculated according to the IEC 61853-1 standard (International Electrotechnical Commission, 2018).

4.3.1. Number of Panels Calculation

$$N_p = \frac{P_{total}}{P_{panel}} \quad (52)$$

- N_p : Total number of panels
- P_{total} : Total system power (W)
- P_{panel} : Power of one panel (W)

Calculation:

$$N_p = \frac{1.049.000}{690} = 1520 \quad (53)$$

Approximately *1520 panels* are required. Extra panels were added due to the width of the land.

4.3.2. Maximum Panels per String

$$N_{string} = \frac{V_{max}}{V_{oc}} \quad (54)$$

- N_{string} : Maximum number of panels in a string
- V_{max} : Maximum input voltage of the inverter (V)
- V_{oc} : Open circuit voltage of the 690W panel (Voc)

Calculation:

$$V_{oc} = 48{,}02 \quad (55)$$

$$N_{string} = \frac{1100}{48{,}02} = 22.90 \quad (56)$$

To ensure safety, we round down to 23 panels per string.

4.3.3. Total Number of Strings

$$N_{total_{string}} = \frac{N_p}{N_{string}} \tag{57}$$

$$N_{total_{string}} = \frac{1520}{23} = 66 \tag{58}$$

Approximately 66 strings are needed.

4.3.4. Strings per MPPT

$$N_{MPPT} = \frac{N_{total_{string}}}{M} \tag{59}$$

- N_{MPPT} : Number of strings per MPPT
- M : Number of MPPTs in the inverter

Calculation:

$$N_{MPPT} = \frac{66}{10} = 66 \tag{60}$$

Exactly 7 strings per MPPT. (Minimum string)

4.3.5. MPPT Input Current

$$I_{MPPT} = N_{MPPT}\ X\ I_{mpp} \tag{61}$$

- I_{MPPT} : Input current per MPPT (A)
- I_{mpp} : Operating current of one 690W panel (A)

Calculation:

$$I_{mpp} = 17.25\ A \tag{62}$$

$$I_{MPPT\_min} = 8\ X\ 17{,}25 = 138\ A \tag{63}$$

$$I_{MPPT\_max} = 10\ X\ 17{,}25 = 172.5\ A \tag{64}$$

This still exceeds the inverter's maximum input current per MPPT (30A), requiring adjustment of the string distribution.

4.3.6. Minimum Number of Panels per String

The minimum number of panels per string is determined by the MPP (Maximum Power Point) voltage range of the inverter.

Formula: $$N_{min_{string}} = \frac{V_{min}}{V_{mpp}} \tag{65}$$

- $N_{\min_{string}}$: Minimum number of panels per string
- V_{min} : Minimum MPP voltage of the inverter (200V from datasheet)
- V_{mpp} : Operating voltage of one panel at MPP (40.01V for 690W panel)

Calculation:

$$N_{min_{string}} = \frac{200}{40.01} \sim 4.99 \tag{66}$$

Rounding up, the minimum number of panels per string is *5*.

- **Summary for Minimum Configuration:**

1. Minimum panels per string: 5
2. Maximum panels per string: 23
3. Minimum strings (to utilize MPPTs): 10
4. Minimum inverters required: 8

Even in a minimal configuration, at least 8 inverters are needed to reach the 1 MW target due to the maximum output limitations of the inverter. Same for a 560W PV panel. As can be seen from the summary above, for a 565W MonoPERC panel this simulation would continue with 19 panels and 8 inverters per array.

4.3.7. Total Panel Count

$$N_p = 19xN_{strings} \tag{67}$$

We need to determine how many strings are required to reach 1 MW.

4.3.8. Total System Power Calculation

$$P_{string} = 19x690 = 13{,}11W\ (13.11\ kW) \tag{68}$$

To reach 1 MW:

$$N_{strings} = \frac{1{,}000{,}000}{13{,}11} = 76{,}277 \tag{69}$$

Approximately *76 strings* are required.

4.3.9. Strings per Inverter

$$N_{strings_{per_{inv}}} = \frac{76}{8} = 9{,}5 \tag{70}$$

Each inverter has 10 MPPTs. If we distribute 13 strings:

$$N_{MPPT} = \frac{9{,}5}{10} = 0{,}95 \tag{71}$$

Since there are 10 mppt and 2 even in the inverter, since it turns out to be 9.5, 1 mppt will remain odd.

4.3.10. Voltage and Current Check

String Voltage (Vmpp and Voc)

$$V_{strings_{mpp}} = 19\ X\ 40.01 = 760.19V \tag{72}$$

$$V_{string_{oc}} = 19\ X\ 48.02 = 912.38V \tag{73}$$

- This falls within the inverter's MPPT range (200-1000V).
- The open-circuit voltage (Voc) is below the inverter's maximum input voltage (1100V).

String Current (Impp and Isc):

$$I_{string_{mpp}} = 17{,}25\ A \tag{74}$$

$$I_{strings_{sc}} = 18{,}26\ A \tag{75}$$

Each MPPT can handle up to 30A per input, meaning two strings in parallel per MPPT is safe.

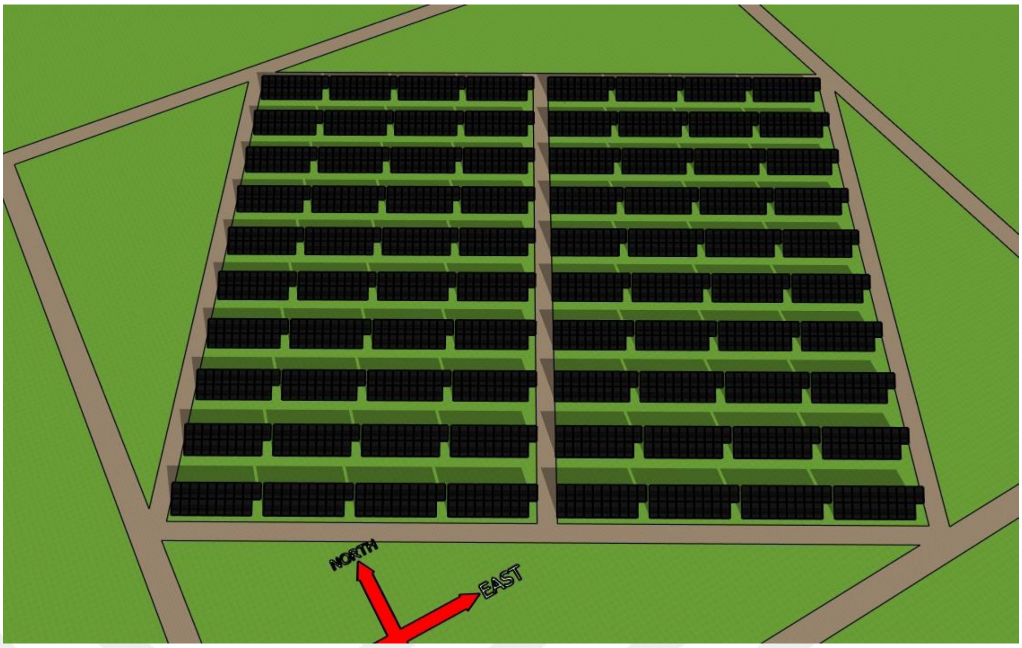


Figure 4.5. Layout of the Bifacial 690W TOPCon Panel System.

Source: Author

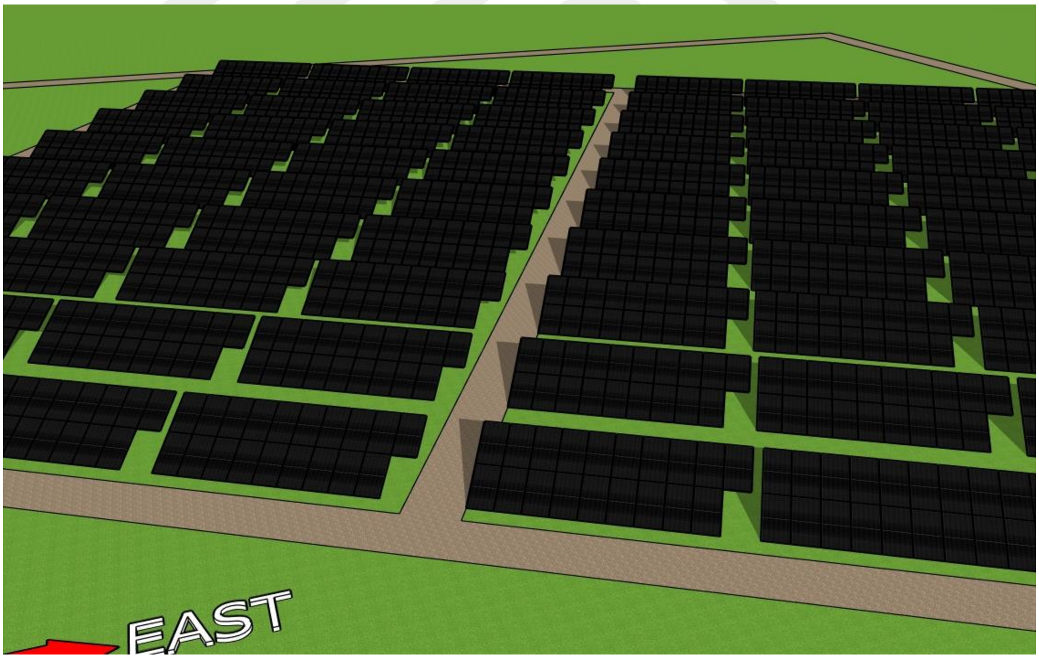


Figure 4.6. 3D Model of the Bifacial 565W TOPCon Panel Design

Source: Author

5. CHAPTER: STORAGE CALCULATIONS

In solar energy systems, storage plays a critical role in ensuring more efficient use of the energy produced, increasing energy supply security and achieving grid independence. Storage systems balance the system by stepping in, especially during hours when energy production decreases or consumption increases.

Energy storage systems are used in various areas such as energy backup, peak shaving, energy balancing, and providing grid services. They ensure continuity of critical loads during grid outages, reduce energy costs by supplying stored power during peak consumption hours, enable nighttime use of solar energy generated during the day, and contribute to grid stability through services like frequency regulation and demand response. There are several types of storage systems, each with specific advantages: lithium-ion batteries offer high energy density and deep discharge capability (80–90% DoD); lead-acid batteries are more affordable but have lower energy density and shorter lifespan (50–60% DoD); flow batteries are ideal for high-capacity and long-term applications; thermal storage systems store heat instead of electricity, making them suitable for industrial use; and hydrogen storage allows long-term energy storage by converting excess energy into hydrogen.

When designing a storage system, several factors must be considered, including system capacity (daily energy production and consumption), required backup time (e.g., 1–2 days), battery type and efficiency (DoD and charge/discharge performance), environmental conditions (temperature sensitivity and operating environment), and cost analysis (initial investment, maintenance, and battery lifespan). The general calculation process begins with identifying the system's energy needs, followed by calculating the required storage capacity in kWh based on backup requirements. The number of batteries is then determined according to the selected battery's capacity, and the overall system voltage is configured to match the operational voltage of the storage system. In addition, system integration with renewable energy sources and monitoring infrastructure should be planned for optimal performance. Ultimately, a well-designed storage system enhances energy reliability, flexibility, and long-term sustainability.

5.1. Energy Produced by the System

The system's daily energy output depends on:

- Total system capacity: 1 MW (1,000 kW)
- Daily average solar radiation: 5 hours/day (typical for Izmir Aliağa)

$$E_{daily} = P_{system}\ x\ H \tag{76}$$

$\boldsymbol{E_{daily}}$ **:** Daily energy produced (kWh)

$\boldsymbol{P_{system}}$: Total system capacity (kW)

$\boldsymbol{H}$ **:** Solar radiation in hours/day

Calculation:

$$E_{daily} = 1000x\ 5 = 5000\frac{kWh}{day} \tag{77}$$

The system produces approximately *5,000 kWh/day*.

5.2. Determining Battery Storage Size

a. Backup Duration

Decide how many days of backup storage is required.

- For *1 day of backup*, the battery must store the system's daily energy output:

$$E_{battery} = E_{daily} = 5000kWh \tag{78}$$

- For *2 days of backup*:

$$E_{battery} = 5000\ x\ 2 = 10\ 000\ kWh \tag{79}$$

b. Depth of Discharge (DoD)

Batteries are not discharged completely to preserve their lifespan. Typical DoD values:

- Lithium-ion: 80-90%
- Lead-acid: 50-60%

For *80% DoD*:

Usable Capacity = $\frac{E_{battery}}{DoD}$ (80)

1 Day Backup:

Usable Capacity = 5,000/0,8 = 6,250 kWh (81)

1 Day Backup:

Usable Capacity = 10,000/0,8 = 12,500 kWh (82)

5.3. Battery Bank Configuration

a. Voltage Selection

Assume a DC bus voltage of 1000V, typical for large-scale systems.

b. Battery Capacity in Ampere-Hours

$$C_{battery} = \frac{Usable\ Capacity\ (kWh)}{Voltage\ (V)} \quad (83)$$

- **1 Day Backup:**

$$C_{battery} = \frac{6{,}250}{1000} = 6.25\ kAh\ (6{,}250\ Ah) \quad (84)$$

- **2 Day Backup:**

$$C_{battery} = \frac{12{,}500}{1000} = 12.5\ kAh\ (12{,}5\ Ah) \quad (85)$$

5.4. Selecting Battery Modules

Suppose you select a battery module with:

- Capacity: *5 kWh*
- Nominal Voltage: *100V*

The number of modules required:

$$N_{module} = \frac{Usable\ Capacity\ (kWh)}{Module\ Capacity\ \ (kWh)} \tag{86}$$

- **1 Days Backup:**

$$N_{module} = \frac{6{,}250}{5} = 1{,}250\ modules \tag{87}$$

- **2 Days Backup:**

$$N_{module} = \frac{12{,}500}{5} = 2{,}500\ modules \tag{88}$$

5.4.1. Summary of Battery Storage:

- **Daily Energy Output:** 5,000 kWh/day
- **1 Day Backup:** 6,250 kWh (6.25 MWh)
  - Battery Capacity: 6,250 Ah at 1000V
  - Modules: 1,250 units of 5 kWh each
- **2 Days Backup:** 12,500 kWh (12.5 MWh)
  - Battery Capacity: 12,500 Ah at 1000V
  - Modules: 2,500 units of 5 kWh each

5.5. Exploring Cost Analysis, Installation Design, and Other Aspects of the Battery System

5.5.1. Cost Analysis

Battery storage is a significant investment in solar energy systems, and costs depend on the following factors:

Battery Type: Lithium-ion batteries are more expensive but offer higher efficiency and lifespan compared to lead-acid batteries.

System Size: The larger the storage (kWh), the higher the cost. Costs typically range from $200 to $400 per kWh for lithium-ion systems.

Additional Components: Battery Management System (BMS), inverters (if separate), and installation labor can add to the cost.

For example:

- 1 Day Backup (6,250 kWh): Estimated cost = $1,250,000- $2,500,000
- Days Backup (12,500 kWh): Estimated cost = $2,500,000- $5,000,000

5.5.2. Installation Design

Space Requirements: Large-scale systems need adequate space, often housed in battery cabinets or containers.

Electrical Layout: Batteries must integrate seamlessly with the PV system and inverters. String inverters or hybrid inverters are preferred for better efficiency.

Cooling Systems: Proper ventilation or cooling mechanisms are required to maintain battery performance and safety.

Safety Measures: Systems should include fire suppression mechanisms and adhere to international safety standards (e.g., UL, IEC).

5.5.3. Benefits of Adding Battery Storage

Energy Independence: Provides backup power during grid outages, ensuring energy continuity.

Peak Shaving: Stores excess energy so it can be used during peak consumption hours, thus reducing electricity costs.

Renewable Energy Maximization: Prevents excess energy generated from going to waste, stores it and maximizes sustainable energy use.

Grid Services: Contributes to grid balance by participating in large-scale systems, frequency regulation and demand response programs.

Emission Reduction: Minimizes environmental impacts by reducing fossil fuel consumption.

Energy Arbitrage: Stores energy during low electricity prices and can be used or sold during high-priced hours.

5.5.4. Challenges

- Initial Costs: Due to the high installation cost and technological advancement of lithium-ion batteries, the return on investment may be extended.
- Maintenance: The average lifespan is between 10-15 years.
- Efficiency Loss: Energy loss of 5-15% may occur during charge-discharge cycles.
- Environmental Concerns: Due to the high environmental impacts of lithium, cobalt and nickel mining, sustainability is difficult due to low recycling rates.
- Safety Risks: Overheating and thermal runaway may pose a risk of fire or explosion.
- Grid Integration: Technical and legal regulations may be required to adapt large-scale battery systems to the existing grid infrastructure.

6. CHAPTER: SIMULATION DATA

6.1. What is PVSyst and How Can It Be Designed?

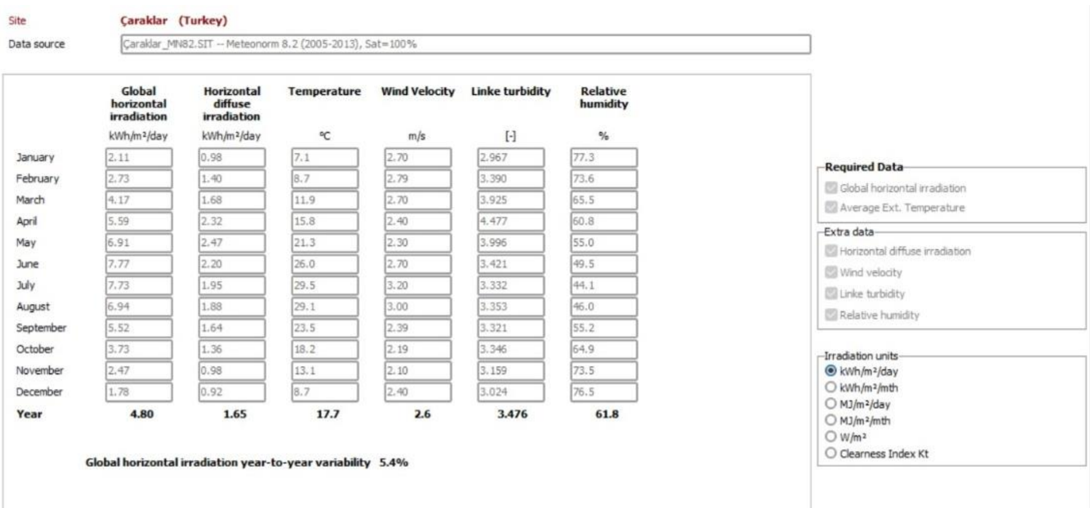
In this study, the most widely used PVSyst program in the solar energy sector was used as a simulation program. In short, PVSyst is a professional software used in the design, simulation and performance analysis of solar energy systems and has been widely used worldwide for both academic research and commercial projects since 1994 (PVSyst SA, 1994). The software analyzes the energy production potential of PV systems in detail by supporting the design of grid-connected, off-grid and hybrid solar energy systems. It offers comprehensive simulations on topics such as annual energy production estimates, system losses (e.g. dust, temperature and cabling losses), shading analyses and component selection. It can check the technical compatibility of solar panels and inverters and provide optimization by calculating battery capacity for storage systems. In addition, it uses regional solar radiation and temperature data by utilizing worldwide meteorological databases (e.g. Meteonorm and NASA), thus allowing for design appropriate to geographical conditions. PVSyst can be used at every stage from feasibility studies to post-installation performance analysis of projects; For this reason, it is preferred by project developers, academics, consulting firms and energy companies. The software, which offers detailed technical reports, annual energy production profiles and 3D visualizations to its users, is quite strong in visuality and technical analysis. In parallel with the development of the solar energy sector, the detailed analyses provided by the software have become an indispensable tool for increasing the reliability of investments and optimizing energy production.

6.2. Aliağa Çoraklar Region Simulation Details

In this study, the production data and technical differences between 3 different PV panels in the Çoraklar region in Aliağa, 560W MonoPERC, 565w TOPCon (TOPCon production starts from 565W) and 690W TOPCon PV panels were examined.

Since the project set-ups will be the same kWp values or close to kWp values, 1818 panels were used for the 560wp panel, 1802 for the 565 wp panel, and 1520 for the 690 wp panel.The inverter used is the same and the AC outputs of the project are considered the same, thus allowing us to make better comments. The inverter brand is Huawei, 8 units of the SUN2000-110KTL-M0 model were used.

Aliağa , Çoraklar region stands out as an ideal location for solar energy projects with its geographical location and climate characteristics. This region, located in the Aegean Region of Turkey, within the borders of the Aliağa district of İzmir province, is located at 38.82° north latitude and 27.08° east longitude. Çoraklar, which has an altitude of approximately 97 meters, draws attention with its high sunshine duration and solar radiation values throughout the year.The region has an annual average global horizontal radiation of 1751 kWh/m² (Meteoroloji Genel Müdürlüğü, 2023), which is above the Turkish average. Climatic conditions, with hot summers and mild winters, are suitable for increasing the efficiency of solar energy systems. In addition, factors such as low humidity and low cloud cover provide more consistent solar energy production throughout the year. Çoraklar's wide and open lands allow for the prevention of shading problems in system installation and more efficient designs. In addition, the region's energy infrastructure and transportation facilities offer advantages that facilitate installation and maintenance processes. For these reasons, the Aliağa Çoraklar region has become a strategic and economical choice for solar energy investments.



Site: Çaraklar (Turkey)
Data source: Çaraklar_MN82.SIT -- Meteonorm 8.2 (2005-2013), Sat=100%

	Global horizontal irradiation kWh/m²/day	Horizontal diffuse irradiation kWh/m²/day	Temperature °C	Wind Velocity m/s	Linke turbidity [-]	Relative humidity %
January	2.11	0.98	7.1	2.70	2.967	77.3
February	2.73	1.40	8.7	2.79	3.390	73.6
March	4.17	1.68	11.9	2.70	3.925	65.5
April	5.59	2.32	15.8	2.40	4.477	60.8
May	6.91	2.47	21.3	2.30	3.996	55.0
June	7.77	2.20	26.0	2.70	3.421	49.5
July	7.73	1.95	29.5	3.20	3.332	44.1
August	6.94	1.88	29.1	3.00	3.353	46.0
September	5.52	1.64	23.5	2.39	3.321	55.2
October	3.73	1.36	18.2	2.19	3.346	64.9
November	2.47	0.98	13.1	2.10	3.159	73.5
December	1.78	0.92	8.7	2.40	3.024	76.5
Year	4.80	1.65	17.7	2.6	3.476	61.8

Global horizontal irradiation year-to-year variability 5.4%

Figure 6.1. Climate Data of the Çoraklar Region

Source: Author

The figure above gives the weather and radiation conditions in the barren region used in the simulation. To explain briefly,

- Global horizontal irradiation (GHI): Daily total solar radiation falling on the horizontal surface (kWh/m²/day).
- Horizontal diffuse irradiation: Daily diffuse solar radiation falling on the horizontal surface (kWh/m²/day).
- Temperature: Average monthly temperature (°C).
- Wind velocity: Average wind speed (m/s).
- Line turbidity: Degree of transparency of the atmosphere ([-] unit).
- Relative humidity: Average relative humidity (%).

This data has been used in the design and analysis of solar energy systems, and the PVSyst application retrieves this data by using the most appropriate source from its library for simulation and uses these values as a background in the design. Because it is important to evaluate the annual energy production potential in a certain region or to examine environmental conditions. This information is obtained by entering the location information before starting the simulation.

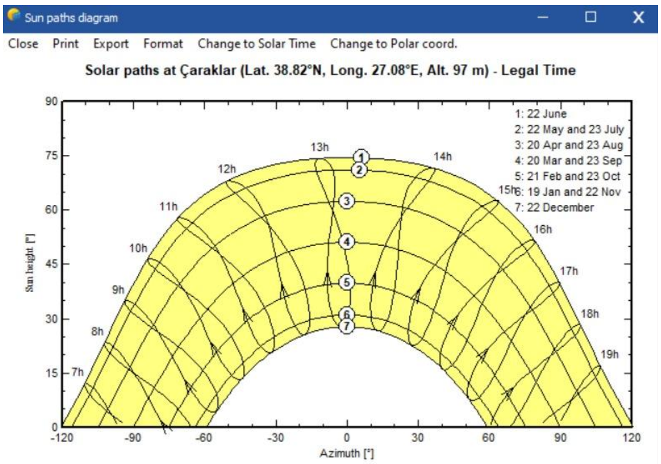


Figure 6.2. Sun Path Diagram

Source: Author

The diagram above visualizes the sun's movement at different times throughout the year in Çoraklar, in terms of solar altitude (angle it makes with the horizon) and azimuth (horizontal direction); the sun's path across the sky on specific dates provides critical information for optimizing energy production and proper placement of solar panels. Following the input of location, climatic data, and solar radiation, system parameters are defined. Among these, the panel tilt angle is a critical input and is incorporated into the simulation accordingly.

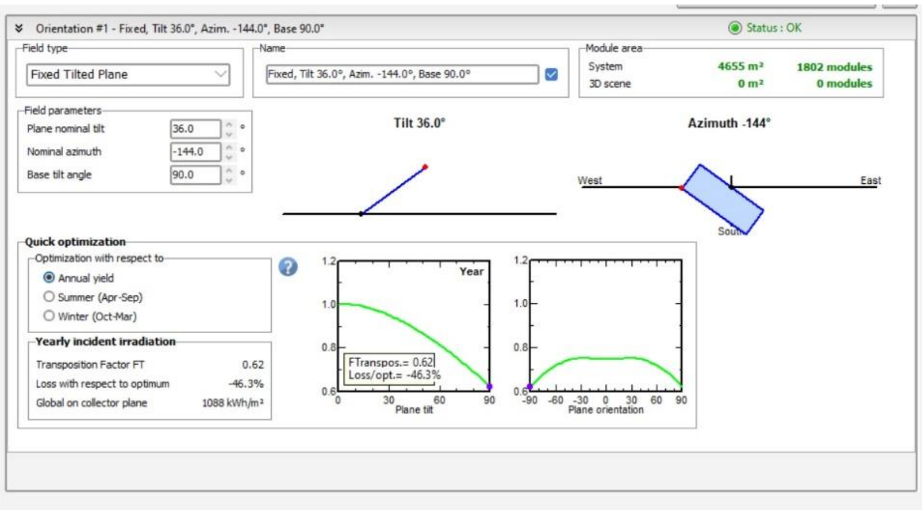


Figure 6.3. Solar Panel Placement Angle and Optimization Input

Source: Author

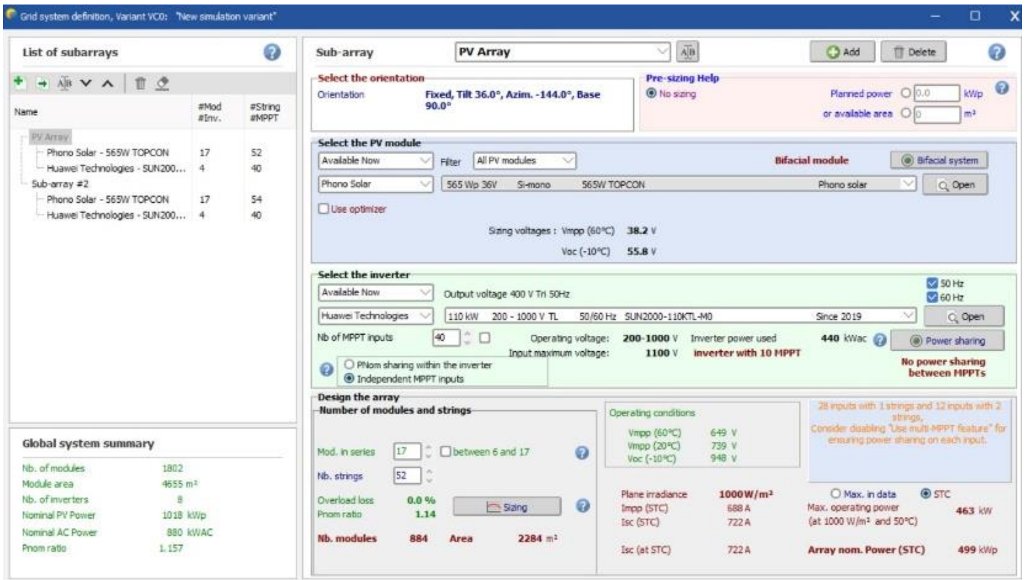


Figure 6.4. PV and Inverter Selection

Source: Author

Finally, the panel model and number to be used in the simulation are entered. String adjustments are made. Similarly, the inverter model and number are entered. The program takes the system losses optimally.

6.3. 560W MonoPERC Bifacial Panel Production Data

Performance and Losses with 560W MonoPERC panels and 1018 kWp capacity, the system generates 923,781 kWh annually, achieving 907 kWh/kWp and a PR of 86.03%. Temperature losses are 3.9%, module quality loss 0.4%, mismatch loss 2.0%, inverter loss 1.7%, and ohmic loss 0.7%, all within optimized design parameters.

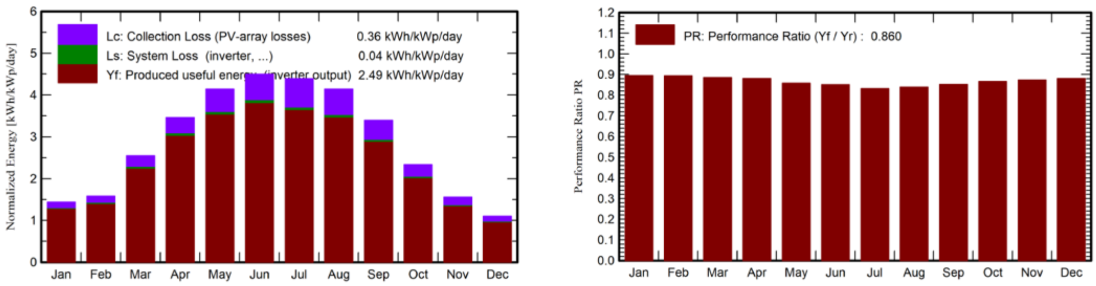


Figure 6.5. Performance Trends of 560W MonoPERC Panel.

Source: Author

The graphs show daily energy production (Yf/kWp), system (Ls) and PV array losses (Lc), with seasonal variations. Monthly PR values indicate consistent and efficient performance year-round

Table 6.1. Balances and Main Results for 560W Monofacial PV

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	E_Grid kWh	PR ratio
January	65.4	30.45	7.14	44.6	42.1	41380	40640	0.895
February	76.4	39.11	8.66	44.3	42.1	41052	40331	0.894
March	129.2	52.20	11.94	79.0	75.3	72429	71179	0.885
April	167.7	69.57	15.77	103.7	99.3	94593	92992	0.881
May	214.2	76.67	21.26	128.3	123.1	114040	112114	0.858
June	233.1	66.00	26.01	135.0	129.5	118829	116848	0.850
July	239.6	60.48	29.46	136.1	130.6	117320	115354	0.833
August	215.1	58.21	29.11	128.4	123.1	111646	109778	0.840
September	165.7	49.23	23.50	101.9	97.4	89941	88426	0.852
October	115.5	42.06	18.21	72.5	68.7	65049	63945	0.867
November	74.2	29.39	13.09	46.7	43.8	42270	41508	0.873
December	55.1	28.46	8.66	34.2	32.1	31242	30667	0.881
Year	1751.3	601.83	17.79	1054.7	1007.0	939789	923781	0.860

Source: Author.

6.3.1. Insolation Values for 560W Monofacial PV

The annual total solar radiation reaching the horizontal plane in Aliağa (GlobHor) was measured as 1751.3 kWh/m², reaching its highest level in June (233.1 kWh/m²) and July (239.6 kWh/m²). Diffuse radiation (DiffHor) is higher in winter months, indicating the effect of cloudy weather conditions. When annual averages are examined, the solar radiation data of Aliağa is at a satisfactory level, suitable for the high solar potential of the Aegean Region.

6.3.2. Panel Production Performance for 560W Monofacial PV

The fact that the 560 W panel array produces a total of 939,789 kWh of energy and transfers 923,781 kWh of energy to the grid shows that the system operates with high efficiency. The system performance ratio (PR) varied between 83% and 89% throughout the year, reaching an overall average of 86%. Efficient use of the radiation (GlobInc) coming to the panel surface and minimizing inverter losses optimized energy production and proved that the technical design of the system was well done. The peak of energy production, especially in the summer months, shows that the system provides maximum benefit from the seasonal conditions in the installation area. These values are an indicator of a successful system both technically and economically. In addition, the project will contribute to reducing the return rate to a short time.

6.4. 565W TOPCon Bifacial Panel Production Data

Performance and Losses with 565W TOPCon panels, an installed capacity of 1018 kWp generated 932,509 kWh annually, achieving a specific production of 916 kWh/kWp and a performance ratio (PR) of 86.84%. Temperature loss was limited to 3.7% and kept under control thanks to the low-temperature coefficient (-0.29%/°C), while module quality loss remained at 0.4%. Module mismatch loss was measured at 2.0%, inverter efficiency loss at 1.6%, and ohmic losses at 0.7%, with minimal losses occurring during energy transmission.

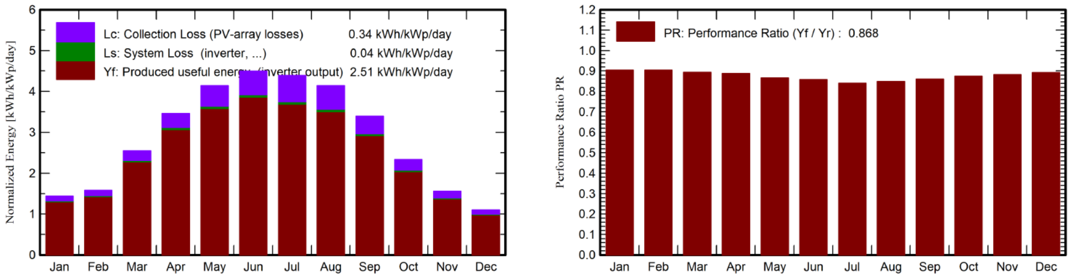


Figure 6.6. Performance Trends of 565W TOPCon Panel

Source: Author

Table 6.2. Balances and Main Results for 565W TOPCon PV

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	E_Grid kWh	PR ratio
January	65.4	30.45	7.14	44.6	42.1	41784	41058	0.904
February	76.4	39.11	8.66	44.3	42.1	41491	40780	0.904
March	129.2	52.20	11.94	79.0	75.3	73080	71850	0.893
April	167.7	69.57	15.77	103.7	99.3	95316	93743	0.888
May	214.2	76.67	21.26	128.3	123.1	115023	113124	0.866
June	233.1	66.00	26.01	135.0	129.5	119874	117922	0.858
July	239.6	60.48	29.46	136.1	130.6	118469	116527	0.841
August	215.1	58.21	29.11	128.4	123.1	112625	110783	0.848
September	165.7	49.23	23.50	101.9	97.4	90713	89221	0.860
October	115.5	42.06	18.21	72.5	68.7	65593	64507	0.874
November	74.2	29.39	13.09	46.7	43.8	42682	41926	0.882
December	55.1	28.46	8.66	34.2	32.1	31637	31068	0.892
Year	1751.3	601.83	17.79	1054.7	1007.0	948287	932509	0.868

Source: Author.

6.4.1. Insolation Values for 565W TOPCon Panel

Total solar radiation (GlobHor) reaching the horizontal plane in the Aliağa region was measured as 1751.3 kWh/m² in total annually, with the highest values seen in June (233.1 kWh/m²) and July (239.6 kWh/m²). These values indicate that insolation potential is at its highest level in the summer months and a significant decrease is experienced in the winter months (December 55.1 kWh/m²). Diffuse radiation (DiffHor) has higher values in the winter months, reflecting cloudy weather conditions.

6.4.2. Panel Production Performance for 565W TOPCon Panel

It is observed that the 565 W TOPCon panel array produces a total of 948,287 kWh of energy annually and transfers 932,509 kWh of energy to the grid. Panel performance remained consistently high throughout the year, with a performance ratio (PR) ranging from 84% to 90%, reaching an annual average of 86.8%. Energy production was at its highest in the summer months, with 117,924 kWh and 116,527 kWh of energy transferred to the grid in June and July, respectively. The low temperature coefficient and high efficiency capacity of TOPCon technology optimized energy production and increased the efficiency of the system, especially in high temperatures during the summer months. These values prove that Aliağa is a suitable region for solar energy projects and that TOPCon panels provide high performance.

6.5. 690W TOPCon Bifacial Panel Production Data

Performance and Losses with 690W TOPCon panels, an installed capacity of 1049 kWp generates 929,715 kWh annually, achieving a specific production of 886 kWh/kWp and a performance ratio (PR) of 84.05%. Temperature loss is at 3.9%, while module quality loss is the highest at 3.0% due to the production tolerances of large-sized panels. Module mismatch loss remained at 2.0%, inverter efficiency loss was recorded at 1.6%, and ohmic losses were measured at 0.7%, effectively managed through system design.

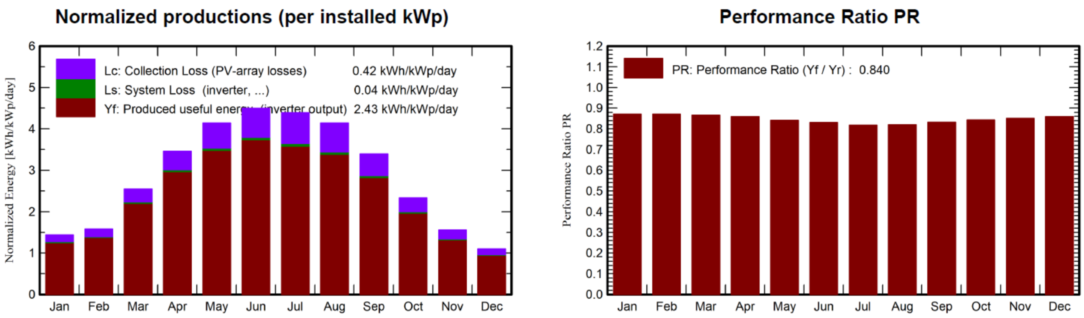


Figure 6.7. Performance Trends of 690W TOPCon Panel.

Source: Author

Table 6.3. Normalized Production and Performance Ratio for 690W TOPCon PV

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	E_Grid kWh	PR ratio
January	65.4	30.45	7.14	44.6	42.1	41485	40777	0.871
February	76.4	39.11	8.66	44.3	42.1	41180	40485	0.871
March	129.2	52.20	11.94	79.0	75.3	72918	71717	0.866
April	167.7	69.57	15.77	103.7	99.3	94934	93408	0.859
May	214.2	76.67	21.26	128.3	123.1	115107	113256	0.841
June	233.1	66.00	26.01	135.0	129.5	119490	117596	0.831
July	239.6	60.48	29.46	136.1	130.6	118541	116653	0.817
August	215.1	58.21	29.11	128.4	123.1	112110	110331	0.819
September	165.7	49.23	23.50	101.9	97.4	90444	88995	0.832
October	115.5	42.06	18.21	72.5	68.7	65126	64072	0.843
November	74.2	29.39	13.09	46.7	43.8	42344	41609	0.850
December	55.1	28.46	8.66	34.2	32.1	31374	30818	0.859
Year	1751.3	601.83	17.79	1054.7	1007.0	945053	929715	0.840

Source: Author.

6.5.1. Insolation Values for 690W TOPCon Panel

Total solar radiation (GlobHor) reaching the horizontal plane in the Aliağa region was measured as 1751.3 kWh/m² in total annually. These values indicate that the solar energy potential is quite good. It reaches the highest levels especially in June and July with 233.1 kWh/m² and 239.6 kWh/m² respectively. In the winter months (December 55.1 kWh/m²), a significant decrease in solar radiation is observed. The annual average temperature of the region is 17.79°C and the effect of seasonal temperature changes on energy production is limited.

6.5.2. Panel Production Performance for 690W TOPCon Panel

The 690 W TOPCon panel array produced a total of 945,053 kWh of energy throughout the year and transferred 929,715 kWh of this to the grid. The performance ratio (PR) varied between 81.7% and 87.1% and the annual average was calculated as 84%. Energy production in the summer months reached its highest levels due to high solar radiation and 117,596 kWh of energy was produced in June. Thanks to the efficient cell technology and low temperature coefficient of TOPCon panels, production performance did not decrease even in high temperatures in the summer months. These production values show that 690 W TOPCon panels work efficiently and that Aliağa is a very suitable region for solar energy projects. This system offers a successful installation example that will provide economic and environmental benefits.

6.6. Comprehensive Analysis of Panel Performance Ratios and Production Values

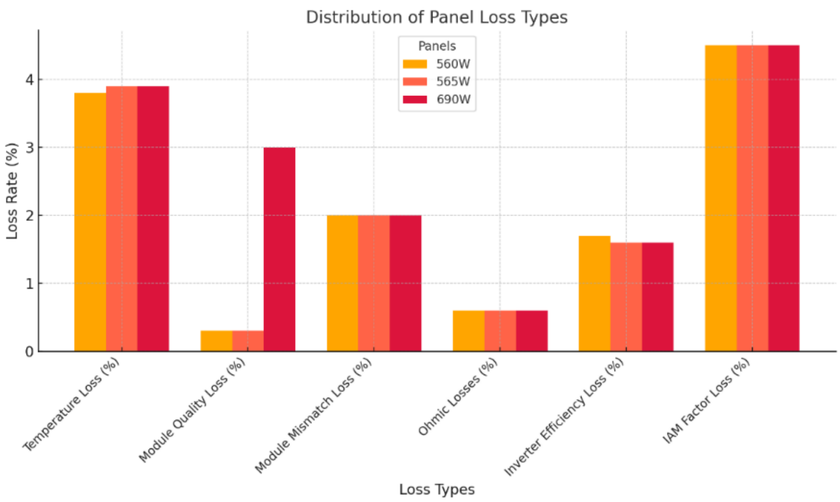
The performance ratios (PR) and annual energy production values of the panels are directly related to the technology used and system design. The 565W TOPCon Bifacial Panel provided the best performance with a PR ratio of 86.84% and an annual production of 932,509 kWh. The low temperature coefficient (-0.29%/°C) and optimized inverter capacity provide superiority especially in hot regions by reducing the temperature loss to 3.7%. At the same time, the module quality loss remained at 0.4%, the module mismatch loss at 2.0%, the IAM loss at 4.5% and the ohmic loss at 0.7%. This effective design and high efficiency made the panel economically advantageous in the long term. The 560W MonoPERC Bifacial Panel stands out as a suitable option for cost-oriented projects with a PR ratio of 86.03% and an annual production of 923,781 kWh. However, the high temperature coefficient (-0.35%/°C) negatively affects efficiency in hot regions and increases the temperature loss to 3.9%. Although IAM loss (4.5%) and module mismatch loss (2.0%) are similar to other panels, ohmic losses (0.7%) and inverter efficiency loss (1.7%) indicate that the design needs further optimization. 690W TOPCon Bifacial Panel, despite its high nominal power, with a PR ratio of 84.05% and an annual production of 929,715 kWh, is affected by module quality losses (3.0%) and large installation space requirements. Although the low temperature coefficient of TOPCon technology (-0.29%/°C) keeps the temperature loss at 3.9%, IAM losses (4.5%) and module mismatch loss (2.0%) are similar to other panels. However, ohmic losses (0.7%) and inverter efficiency loss (1.6%) indicate that the system design may increase the installation costs.

To reduce heat losses, proper ventilation behind panels and low temperature coefficient modules should be used. IAM losses can be minimized with anti-reflective glass and, if possible, sun-tracking systems. Using low-resistance, high-quality cables and minimizing cable lengths reduce ohmic losses. Smaller modules and strict quality control help avoid module quality losses. Matching electrical properties and avoiding shading prevent mismatch losses. Optimizing the DC/AC ratio and proper inverter selection minimize inverter losses. These strategies enhance energy yield and system economics. Analysis shows the 565W TOPCon panel is optimal for performance and cost. The 560W MonoPERC offers cost benefits but lower efficiency in hot climates. The 690W TOPCon may suit high irradiance areas despite its space and quality tradeoffs. This data supports panel selection tailored to project location, energy needs, and budget.

6.7. Loss Factors Affecting Production in the Panel

All panels exhibit comparable loss characteristics, with temperature losses ranging between 3.7% and 3.9%, where the 565W TOPCon panel offers a slight advantage due to its lower temperature coefficient. Module quality loss is significantly higher in the 690W TOPCon panel (3.0%) as a result of larger manufacturing tolerances, while it remains low (0.4%) in the 560W and 565W panels, indicating more consistent production. Module mismatch losses are constant at 2.0% across all systems, reflecting uniform electrical variation among modules. Ohmic losses are also consistent at 0.7%, originating from wiring resistance and potentially increasing in systems with longer cabling. Inverter efficiency losses are optimized, with values of 1.7% for the 560W panel and 1.6% for the 565W and 690W panels. Lastly, IAM losses remain constant at 4.5% in all panels due to the use of identical glass technology, which affects light absorption at non-perpendicular angles.

Table 6.4. Loss Types Rate for 560W Monofacial PV , 565W TOPCon PV and 690W TOPCon PV



Source: Author.

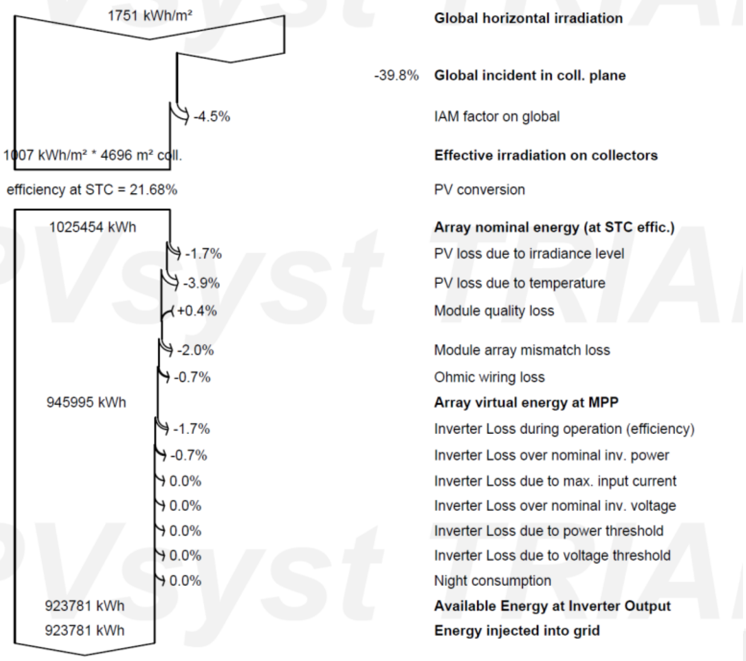


Figure 6.8. The 560W Monofacial Panel Loss Diagram

Source : Author

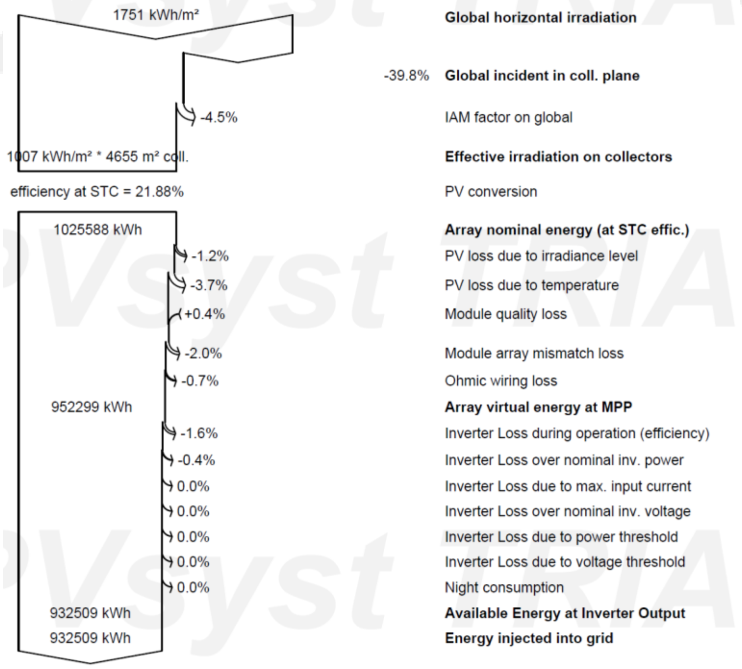


Figure 6.9. The 565W TOPCon Panel Loss Diagram

Source : Author

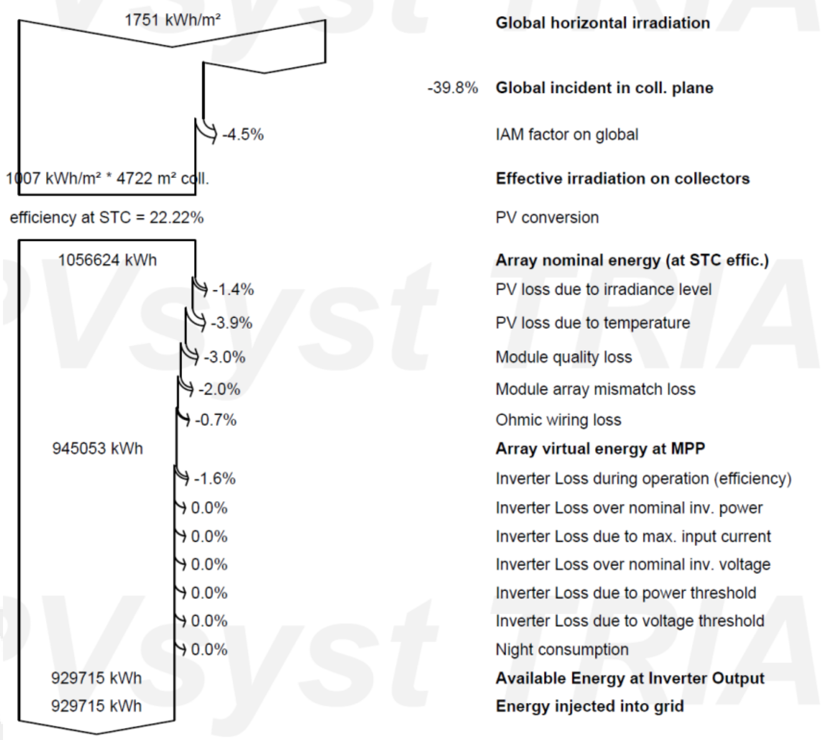


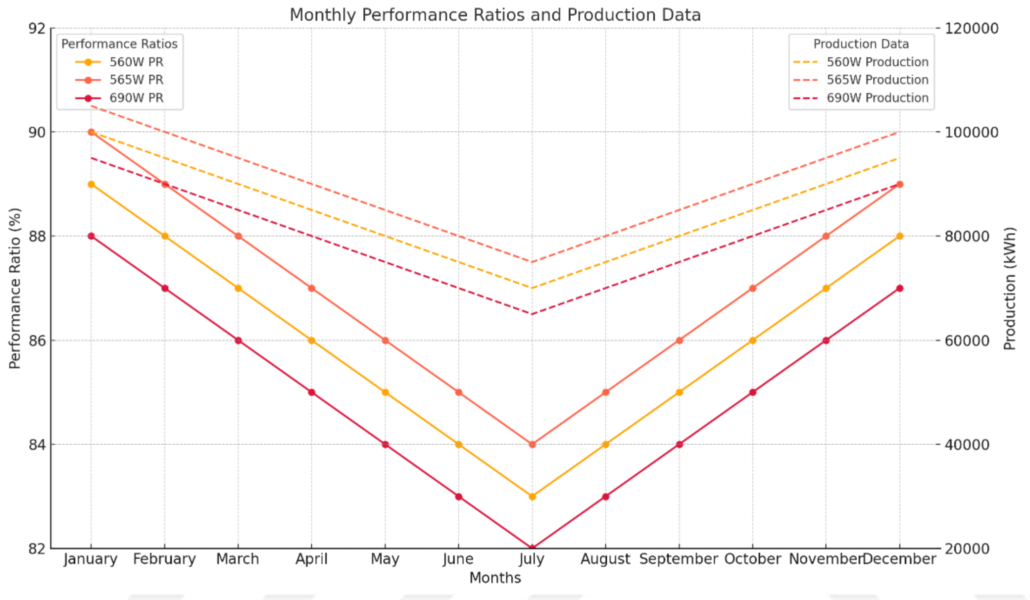
Figure 6.10. The 690W TOPCon Panel Loss Diagram

Source : Author

6.8. Losses in Solar Energy Systems and Reduction Methods

Losses in solar energy systems are caused by various reasons and can be minimized with the right methods. Temperature losses are caused by the panel surface being exposed to high temperatures; these losses can be reduced by choosing panels with low temperature coefficients and ensuring sufficient air flow behind the panels. Module quality losses are related to production tolerances and material quality; certified panels from well-known manufacturers should be used and individual tests should be performed before installation. Module mismatch losses are caused by electrical differences between panels; these losses can be minimized by using panels of the same model and optimizers. Ohmic losses are caused by cable resistance and can be prevented by using low-resistance, appropriately cross-sectioned cables and keeping the cable distance short. Inverter efficiency losses occur during DC-AC conversion; choosing high-efficiency and appropriately sized inverters minimizes losses. IAM factor losses occur when the light does not reach the panel surface at a right angle; correct tilt angle, sun-tracking systems and anti-reflection coated glass surfaces can reduce these losses. Finally, losses due to contamination, shading and physical damage can be kept under control by regular cleaning, shading analysis and continuous monitoring. These methods increase energy production by minimizing losses and improve the economic performance of the system.

Table 6.5. Monthly Performance Ratios and Energy Production of 560W, 565W, and 690W PV Modules



Source: Author

Table 6.8.1. compares the monthly performance ratios (PR) and production values of three different panels. The 565W TOPCon panel maintained the highest performance ratio (up to 90.4%) throughout the year and displayed a regular production graph. Especially in the summer months (May-July), it worked more efficiently than the other panels. The 560W MonoPERC panel provided the best PR value in January with 89.5% and showed a stable performance throughout the year. However, due to the effect of temperature losses, the PR ratio decreased in the summer months. Although the 690W TOPCon panel provided an advantage in production due to its large surface area, due to module quality loss and temperature effects, the PR ratio varied between 87.1% and 81.7% throughout the year and presented the lowest values. In terms of production, all panels provided the highest efficiency in the summer months, while a decrease was observed in the winter months.

6.9. Performance Ratio (PR) and Economic Impacts

Performance ratio (PR) is a critical point that reflects the efficiency of a solar energy system and plays a decisive role in the economic success of the system. A high PR means more energy production; for example, a system with 86% PR provides more energy than a system with 84% PR under the same conditions. This increased energy production shortens the payback period of the investment by increasing electricity sales revenues or saved costs. Every 1% increase in PR provides a significant increase in annual energy production and supports the economic sustainability of the system.

Systems with higher PR reduce installation costs and maintenance costs since they require fewer panels and area to provide the same energy production. This reduces the investment cost per unit of energy (Lazard, 2022) and offers significant advantages in total system costs. LCOE is a metric calculated by dividing the total costs of an energy production facility (capital, operation and maintenance) by the total amount of energy produced over the life of the facility. This metric is an international standard used to compare the cost-effectiveness of different energy production technologies, with systems with higher PR generating more energy with the same installed capacity, saving carbon. In countries with carbon credits, this saving creates additional environmental revenues and provides the potential to benefit more from renewable energy incentives.

A system with a high PR increases energy production, providing a rapid return on investment. In systems with a low PR, the payback period is longer and the economic return is reduced. For example, a 565W TOPCon panel with a PR of 86.84% generates approximately 8,728 kWh more energy per year than a 560W MonoPERC panel with a PR of 86.03%, generating an additional income of $873 per year. This difference translates into a total additional income of $8,730 over a 10-year period.

As a result, a high PR not only increases energy production, but also reduces operating costs, saves carbon, and enables a rapid return on investment. Therefore, optimizing PR in system design and selecting the appropriate technology is critical to the economic sustainability of the investment.

7. CHAPTER: PROJECT TURNAROUND TIME FEASIBILITY AND SUSTAINABILITY

The feasibility study is of critical importance to show to what extent solar energy projects can support economic and environmental sustainability goals. In particular, the amount of solar radiation in the region, the performance of the PV panel technology used, and energy sales prices are the basic elements of this analysis. In this section, we will examine the gray return periods for three different panel types.

7.1. Feasibility Calculation Prepared for 560W MonoPERC Panel

It was prepared to evaluate the feasibility of a 1 MW capacity solar energy system consisting of 560W MonoPERC solar panels planned to be installed in the Aliağa Çoraklar region. Within the scope of the study, annual energy production, investment costs, annual income to be obtained from the electricity sales price and the return on investment period were analyzed. The production data of the project was taken from the simulation.

7.1.1. System Capacity

- Panel Power: 560 W
- Total Power: 1 MW (1,000,000 W)

$$\text{Number of Panels} = \frac{Total\ Power}{Panel\ Powe} = \frac{1000000}{560} = 1768\ panels \quad (89)$$

7.1.2. Annual Energy Production

According to the PV syst report, the production data for 560W 1768 units is

923781 kWh/year.

7.1.3. Revenue Calculation

Assumptions:

- Sale Price (per kWh): 0,13412 USD (EPDK , 2024) 2025 current exchange rate has been taken.
- Annual Revenue: Annual Energy Production x Sale Price
- Annual Revenue: 923781 x 0,13412 = 123897,5 usd/year (90)

7.1.4. Cost Analysis

Initial Investment Cost:

- Panel Cost: 100 usd
- Inverter Cost: 3800 usd
- Other Costs (installation, wiring, labor, permits, etc.): 30% additional cost

Panel Cost = 1786 x 100 =178600 usd (91)

Inverter Cost = 8 x 3800 =30.400 usd (92)

Other Cost = 209000 x 1,30 = 271700 usd (93)

Total Investment = 178600+ 30400 + 271700 = 480700 usd (94)

7.1.5. Return on Investment (ROI)

Return on İnvestment (ROI) is calculated as follow:

$$\text{ROI} = \frac{Total\ Investment}{Annual\ Revenue} \tag{95}$$

$$\text{ROI} = \frac{480700}{123897{,}5} \sim 3{,}87\ year \tag{96}$$

7.1.6. 25 Years of Yield Loss and Performance Analysis

In solar energy projects, photovoltaic (PV) panels used lose performance over time due to various environmental and technical reasons. This study analyzes the efficiency loss and change in energy production in a system consisting of 560W MonoPERC solar panels over a 25-year period.

The system (560W PV panel) experiences an efficiency loss of 0.5% each year (Phono Solar, 2023), which directly affects energy production. The calculations below detail how these losses occur mathematically and how much energy the system will produce at the end of the 25-year period.

$$E_n = E_0 \, x \, (1-r)^n \quad (97)$$

E_0 = 923781 kWh (first year energy productio)

r = 0.005 (Annual loss rate)

n = 25 year

$$E_{25} = 923781 \, x \, (1-0.005)^{25} \quad (98)$$

$$E_{25} = 923781 x \; 0{,}88285 \quad (99)$$

$$E_{25} \sim 815206 \; kWh \quad (100)$$

7.1.7. Total Yield Loss

$$(\%) = (1-(1-r)^n) \text{ x } 100 \quad (101)$$

$$(\%) = (1-0{,}88285) \text{ x } 100 \sim 11{,}72 \quad (102)$$

These results show that the investment has an economically reasonable return on investment and that the region's high solar potential is effectively utilized. In addition, the project will make a significant contribution to reducing carbon emissions in terms of environmental sustainability.

7.2. Feasibility Calculation Prepared for 565W TOPCon Panel

It was prepared to evaluate the feasibility of a 1018,13 kW capacity solar energy system consisting of 565W TOPCon solar panels planned to be installed in the Aliağa Çoraklar region. Within the scope of the study, annual energy production, investment costs, annual income to be obtained from the electricity sales price and the return on investment period were analyzed. The production data of the project was taken from the simulation.

7.2.1. System Capacity

- Panel Power: 565 W
- Total Power: 1,018,130 W

$$\text{Number of Panels} = \frac{Total\ Power}{Panel\ Powe} = \frac{1018130}{565} = 1802\ panels \quad (103)$$

7.2.2. Annual Energy Production

According to the PV syst report, the production data for 565W *1802* units is *932509* kWh/year.

7.2.3. Revenue Calculation

Assumptions:

- Sale Price (per kWh): 0,13412 USD (EPDK , 2024) 2025 current exchange rate has been taken.
- Annual Revenue: Annual Energy Production x Sale Price
- Annual Revenue: 932509 x 0,13412 = 125068 usd/year

7.2.4. Cost Analysis

Initial Investment Cost:

- Panel Cost: 100 usd
- Inverter Cost: 3800 usd

- Other Costs (installation, wiring, labor, permits, etc.): 30% additional cost

Panel Cost = 1802 x 100 =180200 usd (104)

Inverter Cost = 8 x 3800 =30.400 usd (105)

Other Cost = 210600 x 1,3 = 273780 usd (106)

Total Investment = 178600+ 30400 + 273780 = 482780 usd (107)

7.2.5. Return on Investment (ROI)

Return on İnvestment (ROI) is calculated as follow:

$$\text{ROI} = \frac{Total\ Investment}{Annual\ Revenue} \tag{108}$$

$$\text{ROI} = \frac{482780}{125068} \sim 3{,}86 year \tag{109}$$

7.2.6. 25 Years of Yield Loss and Performance Analysis

In solar energy projects, photovoltaic (PV) panels used lose performance over time due to various environmental and technical reasons. This study analyzes the efficiency loss and change in energy production in a system consisting of 565W TOPcon solar panels over a 25-year period.

The system (565W PV panel) experiences an efficiency loss of 0.4% each year (Phono Solar, 2023), which directly affects energy production. The calculations below detail how these losses occur mathematically and how much energy the system will produce at the end of the 25-year period.

$$E_n = E_0\ x\ (1 - r)^n \tag{110}$$

E_0 = 932509 kWh (first year energy productio)

r = 0.004 (Annual loss rate)

n = 25 year

$$E_{25} = \ 932509\ x\ (1 - 0.004)^{25} \tag{111}$$

$$E_{25} = 932509\ x\ 0{,}904 \tag{112}$$

$$E_{25} \sim 842486\ kWh \tag{113}$$

7.2.7. Total Yield Loss

$$(\%) = \ (1 - (1 - r)^{n})\ \text{x}\ 100 \tag{114}$$

$$(\%) = \ (1 - 0{,}904)\ \text{x}\ 100 \sim 9{,}6 \tag{115}$$

7.3. Feasibility Calculation Prepared for 690W TOPCon Panel

It was prepared to evaluate the feasibility of a 1048,80 kW capacity solar energy system consisting of 690W TOPCon solar panels planned to be installed in the Aliağa Çoraklar region. Within the scope of the study, annual energy production, investment costs, annual income to be obtained from the electricity sales price and the return on investment period were analyzed. The production data of the project was taken from the simulation.

7.3.1. System Capacity

- Panel Power: 690 W
- Total Power: 1,048,800 W

$$\text{Number of Panels } = \frac{Total\ Power}{Panel\ Powe} = \frac{1048800}{690} = 1520\ panels \tag{116}$$

7.3.2. Annual Energy Production

According to the PV syst report, the production data for 690W 1520 units is

929715 kWh/year.

7.3.3. Revenue Calculation

Assumptions:

- Sale Price (per kWh): 0,13412 USD (EPDK , 2024) 2025 current exchange rate has been taken.
- Annual Revenue: Annual Energy Production x Sale Price
- Annual Revenue: 929715 x 0,13412 = 124693 usd/year

7.3.4. Cost Analysis

Initial Investment Cost:

- Panel Cost: 100 usd
- Inverter Cost: 3800 usd
- Other Costs (installation, wiring, labor, permits, etc.): 30% additional cost

Panel Cost = 1520 x 100 =152000 usd (117)

Inverter Cost = 8 x 3800 =30.400 usd (118)

Other Cost = 182400 x 1,3 = 237120 usd (119)

Total Investment = 152000 + 30400 + 237120 = 419520 usd (120)

7.3.5. Return on Investment (ROI)

Return on İnvestment (ROI) is calculated as follow:

$$\text{ROI} = \frac{Total\ Investment}{Annual\ Revenue} \tag{121}$$

$$\text{ROI} = \frac{419520}{124693} \sim 3{,}36\ year \tag{122}$$

7.3.6. 25 Years of Yield Loss and Performance Analysis

In solar energy projects, photovoltaic (PV) panels used lose performance over time due to various environmental and technical reasons. This study analyzes the efficiency loss and change in energy production in a system consisting of 690W TOPCon solar panels over a 25-year period.

The system (690W PV panel) experiences an efficiency loss of 0.4% each year (Phono Solar, 2023), which directly affects energy production. The calculations below detail how these losses occur mathematically and how much energy the system will produce at the end of the 25-year period.

$$E_n = E_0 \ x \ (1 - r)^n \quad (123)$$

E_0 = 929715 kWh (first year energy productio)

r = 0.004 (Annual loss rate)

n = 25 year

$$E_{25} = 929715 \ x \ (1 - 0.004)^{25} \quad (124)$$

$$E_{25} = 929715 \ x \ 0{,}904 \quad (125)$$

$$E_{25} \sim 840462{,}36 \ kWh \quad (126)$$

7.3.7. Total Yield Loss

$$(\%) = (1 - (1 - r)^n) \ \text{x} \ 100 \quad (127)$$

$$(\%) = (1 - 0{,}904) \ \text{x} \ 100 \sim 9{,}6 \quad (128)$$

7.4. Comparison of Feasibility Results

The long-term energy production performances of 560W, 565W, and 690W photovoltaic (PV) panels are illustrated in the graphs below. The annual efficiency loss was determined as 0.5% for 560W panels and 0.4% for advanced TOPCon panels (565W and 690W) (Phono Solar, 2023). While the production values are based on experimental data, environmental factors and climate change may cause further reductions in the long term. These simulations provide a valuable comparison of panel technologies and their economic advantages. The production data was derived from MATLAB code (Appendix 5: MATLAB Codes).

Table 7.1. provides detailed comparisons of 25-year production data for 560W MonoPERC, **Table 7.2.** for 565W TOPCon and **Table 7.3.** for 690W TOPCon panels.

Year	Energy Production For 560W (kWh)
1	923781
2	919162
3	914566
4	909993
5	905443
6	900916
7	896412
8	891930
9	887470
10	883033
11	878617
12	874224
13	869853
14	865504
15	861176
16	856871
17	852586
18	848323
19	844082
20	839861
21	835662
22	831484
23	827326
24	823190
25	819074

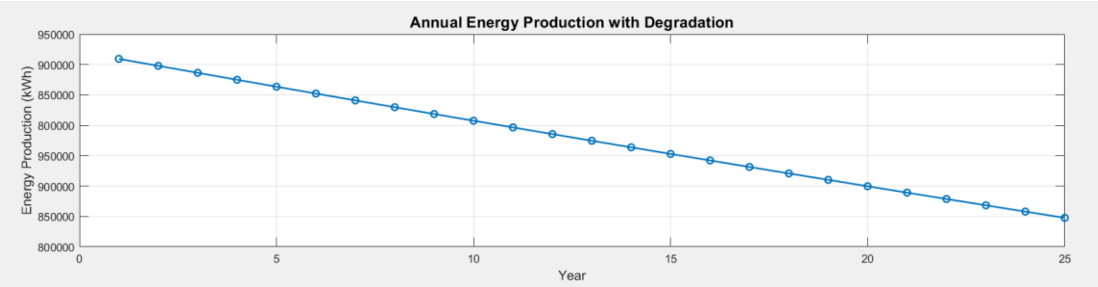
Year	Energy Production For 565W (kWh)
1	932509
2	928779
3	925063
4	921363
5	917678
6	914007
7	910351
8	906710
9	903083
10	899471
11	895873
12	892289
13	888720
14	885165
15	881625
16	878098
17	874586
18	871088
19	867603
20	864133
21	860676
22	857233
23	853805
24	850389
25	846988

Year	Energy Production For 690W (kWh)
1	929715
2	925996
3	922292
4	918603
5	914929
6	911269
7	907624
8	903993
9	900377
10	896776
11	893189
12	889616
13	886057
14	882513
15	878983
16	875467
17	871965
18	868478
19	865004
20	861544
21	858097
22	854665
23	851246
24	847841
25	844450

Source: Author

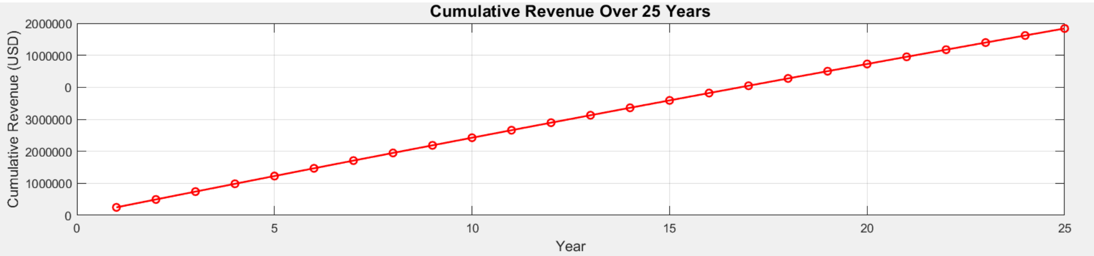
These tables provide insight into long-term investment decisions by revealing the efficiency loss that each panel is exposed to over time and its total energy production capacity. In particular, they contribute to the cost-effectiveness analysis of different panel types and provide important data on which technology may be more advantageous in terms of sustainable energy investments. In this context, the findings of the study are of a guiding nature in the planning of renewable energy projects, in determining the optimum panel selection and for the simulataneous estimation of energy production.

Table 7.4. Annual Energy Production with Degradation



Source: Author

Table 7.5. Cumulative Revenue Over 25 Years



Source: Author

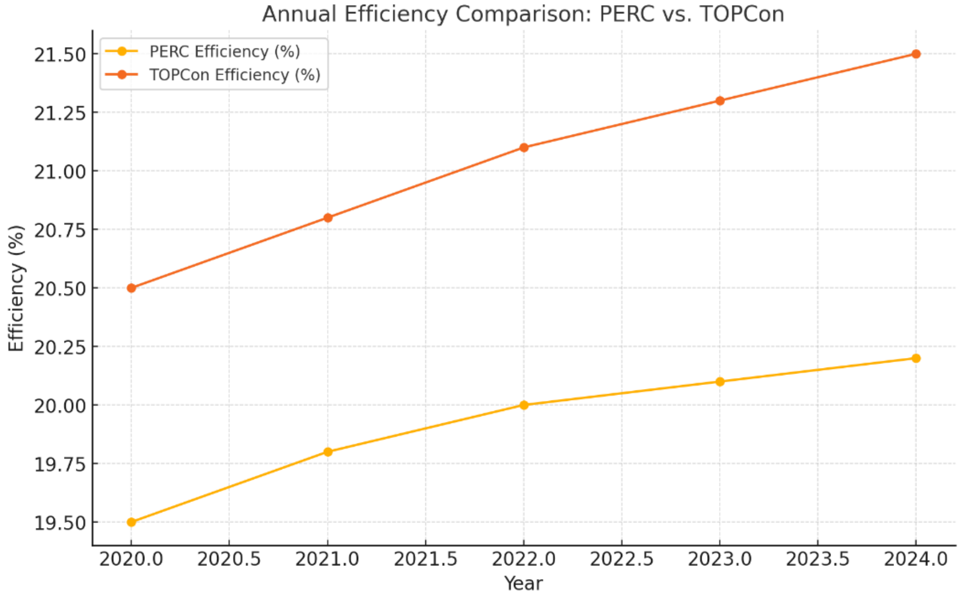
Graph 1 shows that the annual energy production of photovoltaic panels decreases every year. This decrease is attributed to an annual efficiency loss of 0.5% in 560W panels and 0.4% in 565W and 690W TOPCon panels. As a result, at the end of 25 years, energy production decreases by approximately 11-12% compared to the initial value. Graph 2 shows that the cumulative income increases continuously and grows linearly over 25 years. The fixed electricity unit price has limited effect on the growth rate of income despite the decrease in energy production. This situation ensures that the total income of the system reaches a very high level at the end of 25 years and makes the investment economically advantageous. When these two graphs are evaluated together, it is seen that the long-term energy production and economic return of the panels provide a critical decision-making tool for projects.

8. CHAPTER: CONCLUSION

This study conducted a comprehensive comparison between three different photovoltaic (PV) panel types—560W Monocrystalline PERC, 565W TOPCon, and 690W TOPCon—in Aliağa Çoraklar, one of the regions with high solar energy potential in Turkey and analyzed the performance of PV technologies and their contributions to sustainable energy production in detail. The PVSyst simulations used in the study revealed significant differences between panel technologies in terms of energy efficiency, temperature resistance, and cost effectiveness. 690W TOPCon panels reached the highest energy production capacity with their innovative tunnel oxide layer and double-sided usage features and showed the most stable performance against seasonal changes with their high temperature resistance. 565W TOPCon panels, on the other hand, stood out in terms of cost effectiveness while offering a balanced solution in the long term with their low temperature coefficient and high energy conversion rate. 560W Monocrystalline PERC panels have maintained their place as an economical alternative for small and medium-sized projects with their more affordable structure. The study showed that the Aliağa Çoraklar region offers an ideal testing ground for large-scale solar energy projects thanks to its high solar radiation, low humidity and sunny days throughout the year. Considering the regional characteristics, the simulation results confirmed the high energy production potential of PV systems in this region. The performance results of three different panel types reveal that PV technologies play a critical role not only in terms of technical efficiency but also in terms of their economic and environmental contributions to achieving sustainable energy targets.

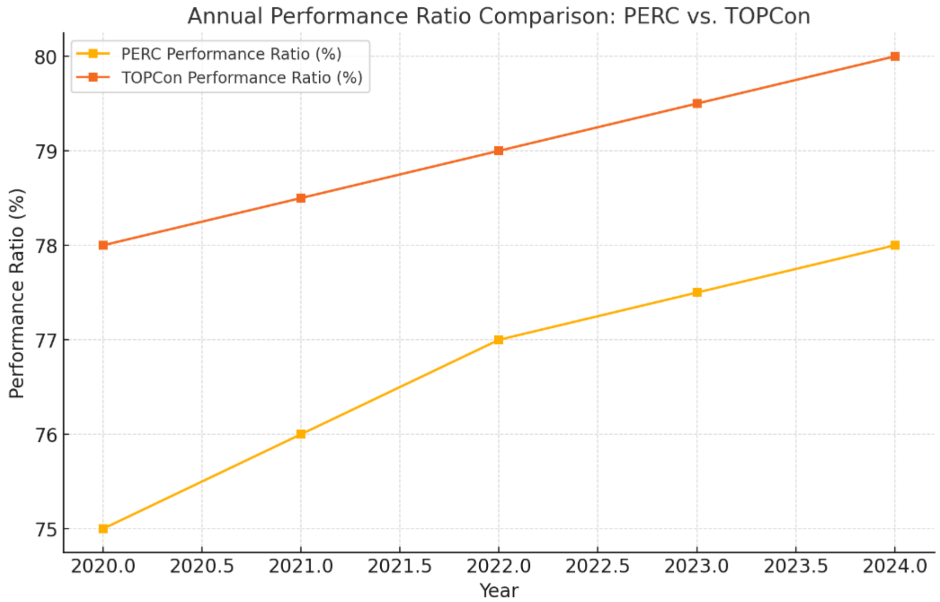
The following visualizations provide a detailed comparison of the annual efficiency and performance ratio of PERC and TOPCon technologies, which were highlighted in the study:

Table 8.1. Annual Efficiency Comparison



Source: Author

Table 8.2. Annual Performance Ratio Comparison

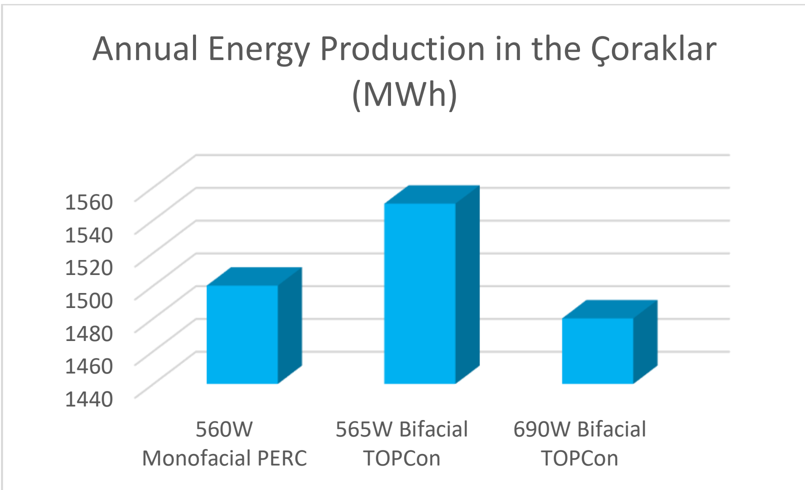


Source: Author

With regard to sustainable energy targets, this study has clearly demonstrated the effectiveness of advanced PV technologies in reducing carbon emissions and their contribution to energy independence. TOPCon panels have offered significant advantages in sustainable energy production with their long-life structures, high efficiencies and low temperature coefficients. In line with Turkey's goals of increasing its renewable energy capacity, the dissemination of these technologies can reduce energy imports, increase energy supply security and also have the potential to create a workforce that will contribute to the local economy.

One key observation from the study is that despite its higher power rating, the 690W TOPCon panel exhibited slightly lower annual energy production compared to the 560W PERC panel. This can be attributed to several factors, including increased panel spacing requirements due to the larger size, which reduces the overall panel density per unit area. Additionally, larger panels are more susceptible to shading losses, as they can cast shadows on adjacent modules, leading to reduced energy capture. The temperature coefficient also plays a significant role; higher power panels often have a greater sensitivity to temperature variations, leading to higher efficiency losses in hot climates. Furthermore, mismatch losses between modules in a string can increase due to voltage and current variations, reducing the overall system efficiency. Finally, some inverter systems may not fully utilize the additional power output of the 690W panel due to operational constraints, further impacting energy production. These combined factors demonstrate that while panel wattage is a critical determinant of energy output, system design considerations and environmental influences must also be taken into account for optimal PV performance.

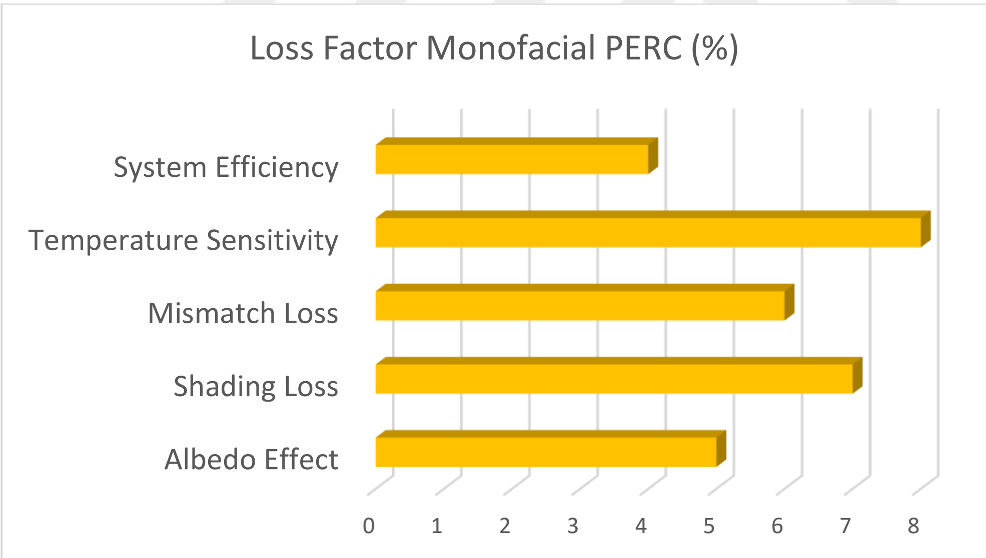
Table 8.3. Annual Performance Ratio Comparison



Source: Author

In addition to these factors, another crucial aspect influencing energy production is the difference between monofacial and bifacial panel technologies. While monofacial panels, such as the 560W PERC model, capture sunlight only from their front surface, bifacial panels like TOPCon can harness reflected sunlight from their rear surface as well. This bifacial gain can significantly enhance energy production in environments with high albedo surfaces, such as snowy, sandy, or concrete-covered areas. However, in locations where albedo is low, the advantage of bifacial panels is diminished, making monofacial panels a more predictable option in terms of output stability. Additionally, monofacial panels typically experience fewer shading and mismatch losses due to their simpler electrical configuration, which can contribute to a more stable energy yield under varying environmental conditions. These distinctions emphasize that panel selection should not be based solely on wattage but also on site-specific conditions, ensuring an optimized balance between cost, efficiency, and long-term performance.

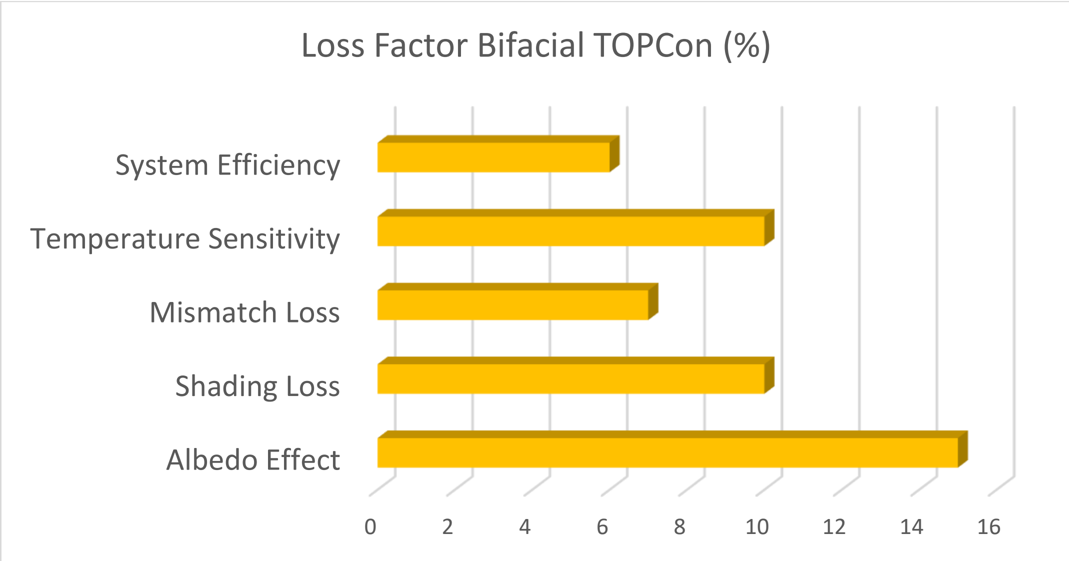
Table 8.4. Loss Monofacial PERC



Source: Author

Loss factors affecting the performance of monofacial PERC panels. The most significant losses occur due to temperature sensitivity and shading, highlighting the impact of environmental factors on monofacial panel efficiency.

Table 8.5. Loss factors affecting the performance of bifacial TOPCon panels.



Source: Author

The albedo effect contributes significantly to bifacial performance, making installation surface properties crucial for maximizing energy yield.

In future studies, it is recommended to verify simulation data with long-term measurements of field performance of PV technologies, integrate innovative energy storage solutions and analyze the environmental impacts of PV systems in more detail. In addition, further optimization of the production processes of TOPCon technologies will allow for cost reduction and more widespread use of these technologies. Studies on innovative cell structures and production processes that will further increase the energy production capacities of advanced PV technologies can maximize the future potential of solar energy. In conclusion, this study reveals the potential of PV technologies in increasing energy production capacity and economic efficiency, while once again emphasizing the strategic importance of these technologies in achieving renewable energy targets. The selection and use of PV technologies suitable for project requirements play a critical role in terms of both economic and environmental sustainability. With the widespread use of advanced PV technologies, Turkey can achieve its renewable energy targets more quickly, effectively and sustainably.

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APPENDICES

APPENDIX 1. PHONO SOLAR BİFACİAL MODULES DATASHEETS

Electrical Typical Values

Model		PS540M8-24/TH		PS545M8-24/TH		PS550M8-24/TH		PS555M8-24/TH		PS560M8-24/TH	
Model	1000V	PS540M8-24/TH		PS545M8-24/TH		PS550M8-24/TH		PS555M8-24/TH		PS560M8-24/TH	
	1500V	PS540M8H-24/TH		PS545M8H-24/TH		PS550M8H-24/TH		PS555M8H-24/TH		PS560M8H-24/TH	
Testing Condition		STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT
Rated Power (Pmpp)		540	402	545	405	550	409	555	413	560	417
Rated Current (Impp)		13.06	10.55	13.15	10.63	13.24	10.70	13.33	10.77	13.42	10.84
Rated Voltage (Vmpp)		41.35	38.07	41.45	38.16	41.55	38.25	41.64	38.34	41.73	38.42
Short Circuit Current (Isc)		13.62	11.00	13.72	11.09	13.82	11.17	13.92	11.25	14.02	11.33
Open Circuit Voltage (Voc)		49.39	46.62	49.49	46.72	49.59	46.81	49.69	46.91	49.79	47.00
Module Efficiency (%)		20.90		21.10		21.29		21.48		21.68	

STC(Standard Testing Conditions): Irradiance 1000W/m², AM 1.5, Cell Temerature 25°C

NOCT (Nominal Operation Cell Temperature): Irradiance 800W/m², Ambient Temperature 20°C , Spectra at AM1.5, Wind at 1m/s

Electrical Characteristics With Different Power Bin

5%	Maximum Power (W)	559	564	569	574	580
	Module Efficiency (%)	21.64	21.84	22.04	22.24	22.44
15%	Maximum Power (W)	597	602	608	613	619
	Module Efficiency (%)	23.10	23.31	23.53	23.74	23.95
25%	Maximum Power (W)	635	640	646	652	658
	Module Efficiency (%)	24.56	24.79	25.02	25.24	25.47

Mechanical Characteristics

Cell Type	Monocrystalline 182mm x 91mm
Dimension (L × W × H)	Length: 2278mm (89.69 inch) Width: 1134mm (44.65 inch) Height: 35mm (1.38 inch)
Weight	28.0kg (61.72 lbs)
Glass	3.2mm Toughened Glass
Frame	Anodized Aluminium Alloy
Cable (Including Connector)	4mm² (IEC), (+): 450mm,(-): 250mm or Customized Length *The requested cable length must be specified before the offer.
Junction Box	IP 68 Rated

Temperature Ratings

Voltage Temperature Coefficient	-0.28%/°C
Current Temperature Coefficient	+0.05%/°C
Power Temperature Coefficient	-0.35%/°C
Tolerance	0~+5w
NOCT	45±2°C
Bifaciality	70±5%

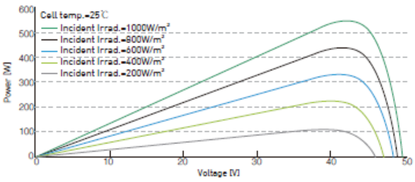
Absolute Maximum Rating

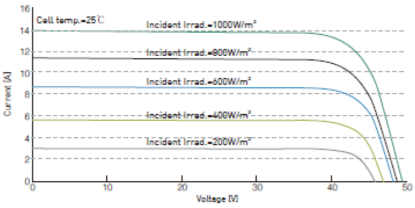
Operating Temperature	From -40 to + 85°C
Hail Diameter @ 80km/h	Up to 25mm
Front Side Maximum Static Loading	5400Pa
Rear Side Maximum Static Loading	2400Pa
Maximum Series Fuse Rating	30A
PV Module Classification	II
Fire Rating (IEC61730)	C
Maximum System Voltage	DC 1000V/1500V

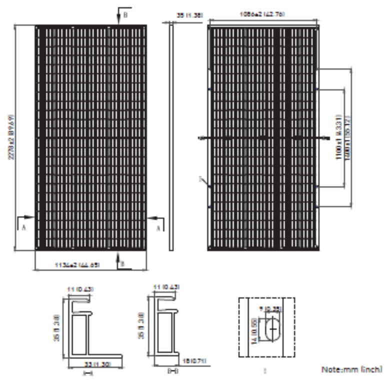
Packing Configuration

Container	20' GP	40' HQ
Pieces/Container	155	620

Electrical Characteristics







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APPENDIX 2. PHONO SOLAR TOPCON MODULES DATASHEETS

Electrical Typical Values

Model											
Model	1000V	PS565M8GF-24/TNH		PS570M8GF-24/TNH		PS575M8GF-24/TNH		PS580M8GF-24/TNH		PS585M8GF-24/TNH	
	1500V	PS565M8GFH-24/TNH		PS570M8GFH-24/TNH		PS575M8GFH-24/TNH		PS580M8GFH-24/TNH		PS585M8GFH-24/TNH	
Testing Condition		STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT
Rated Power (Pmpp)		565	433	570	436	575	440	580	444	585	448
Rated Current (Impp)		13.24	10.66	13.30	10.71	13.36	10.76	13.42	10.81	13.48	10.86
Rated Voltage (Vmpp)		42.68	40.57	42.86	40.74	43.04	40.92	43.22	41.09	43.40	41.26
Short Circuit Current (Isc)		13.89	11.19	13.95	11.24	14.04	11.31	14.11	11.36	14.18	11.42
Open Circuit Voltage (Voc)		51.49	49.30	51.73	49.53	52.20	49.98	52.44	50.21	52.68	50.44
Module Efficiency (%)		21.87		22.07		22.26		22.45		22.65	

STC(Standard Testing Conditions): Irradiance 1000W/m², AM 1.5, Cell Temperature 25°C

NOCT (Nominal Operation Cell Temperature): Irradiance 800W/m², Ambient Temperature 20°C , Spectra at AM1.5, Wind at 1m/s

BSTC**

Maximum Power (Pmax)	620	625	630	635	640
Optimum Operating Current (Impp)	14.53	14.58	14.64	14.69	14.75
Optimum Operating Voltage (Vmpp)	42.68	42.86	43.04	43.22	43.40
Short Circuit Current (Isc)	15.24	15.29	15.28	15.33	15.38
Open Circuit Voltage (Voc)	51.49	51.73	52.20	52.44	52.68

**BSTC:Front Side Irradiation 1000W/m², Back Side Reflection Irradiation 135W/m² , AM 1.5, Ambient Temperature 25°C

Mechanical Characteristics

Cell Type	N Type Monocrystalline
Dimension (L × W × H)	Length: 2278mm (89.69 inch) Width: 1134mm (44.65 inch) Height: 30mm (1.18 inch)
Weight	32.0kg (70.55 lbs)
Glass	2.0mm/2.0mm toughened glass
Frame	Anodized Aluminium Alloy
Cable (Including Connector)	4mm² (IEC), (+): 450mm,(-): 250mm or Customized Length
Junction Box	IP 68 Rated

Temperature Ratings

Voltage Temperature Coefficient	-0.25%/°C
Current Temperature Coefficient	+0.04%/°C
Power Temperature Coefficient	-0.29%/°C
Power Tolerance	0~+3%
NOCT	42±2°C
Bifaciality	80±5%

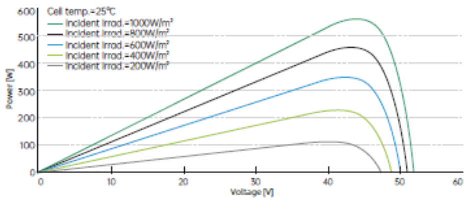
Absolute Maximum Rating

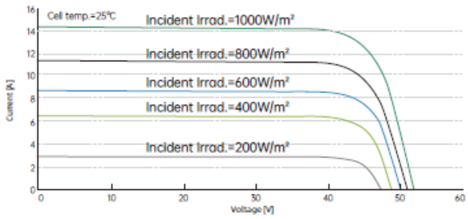
Operating Temperature	From -40 to + 85°C
Hail Diameter @ 80km/h	Up to 25mm
Front Side Maximum Static Loading	5400Pa
Rear Side Maximum Static Loading	2400Pa
Maximum Series Fuse Rating	30A
PV Module Classification	II
Fire Rating (IEC61730)	C
Maximum System Voltage	DC 1000V/1500V

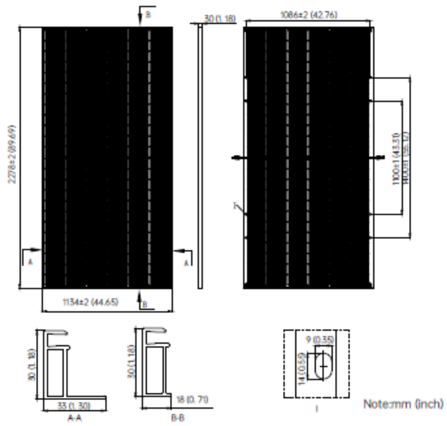
Packing Configuration

Container	20' GP	40' HQ
Pieces/Container	180	720
Pcs/Pallet	36	36
Pallets/Container	5	20

Electrical Characteristics







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APPENDIX 3. PHONO SOLAR TOPCON MODULES DATASHEETS

Electrical Typical Values

Model	PS690M13GFH-22/WNH		PS695M13GFH-22/WNH		PS700M13GFH-22/WNH		PS705M13GFH-22/WNH		PS710M13GFH-22/WNH	
Testing Condition	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT
Rated Power (Pmpp)	690	526	695	530	700	534	705	538	710	542
Rated Current (Impp)	17.25	14.02	17.30	14.06	17.35	14.10	17.40	14.14	17.45	14.18
Rated Voltage (Vmpp)	40.01	37.54	40.20	37.72	40.39	37.90	40.58	38.08	40.76	38.26
Short Circuit Current (Isc)	18.26	14.72	18.32	14.77	18.38	14.82	18.44	14.87	18.50	14.92
Open Circuit Voltage (Voc)	48.02	46.22	48.22	46.41	48.42	46.60	48.62	46.79	48.82	46.98
Module Efficiency (%)	22.21		22.37		22.53		22.70		22.86	

STC(Standard Testing Conditions): Irradiance 1000W/m², AM 1.5, Cell Temperature 25°C

NOCT (Nominal Operation Cell Temperature): Irradiance 800W/m², Ambient Temperature 20°C , Spectra at AM1.5, Wind at 1m/s

BNPI

Maximum Power (Pmax)	759	765	770	776	781
Optimum Operating Current (Impp)	18.96	19.01	19.06	19.11	19.16
Optimum Operating Voltage (Vmpp)	40.12	40.31	40.50	40.69	40.88
Short Circuit Current (Isc)	20.09	20.16	20.22	20.29	20.35
Open Circuit Voltage (Voc)	48.13	48.33	48.53	48.73	48.93

BNPI:Front side irradiation 1000W/m², back side reflection irradiation 135W/m², AM 1.5, ambient temperature 25°C

Mechanical Characteristics

Cell Type	N Type Monocrystalline
Dimension (L × W × H)	Length: 2384mm (93.86 inch) Width: 1303mm (51.30 inch) Height: 33mm (1.30 inch)
Weight	37.7kg (83.11 lbs)
Glass	2.0mm/2.0mm Heat Strengthened Glass
Frame	Anodized Aluminium Alloy
Cable (Including Connector)	4mm² (IEC), (+): 350mm,(-): 250mm or Customized Length
Junction Box	IP 68 Rated

Temperature Ratings

Voltage Temperature Coefficient	-0.25%/°C
Current Temperature Coefficient	+0.048%/°C
Power Temperature Coefficient	-0.29%/°C
Power Tolerance	0~+3%
NOCT	42±2°C
Bifaciality	80±5%

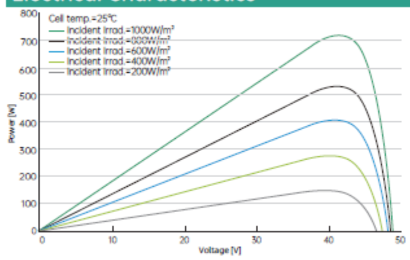
Absolute Maximum Rating

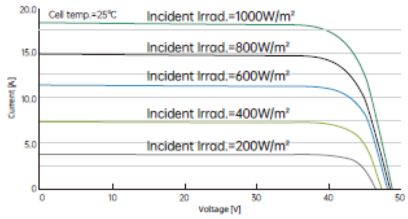
Operating Temperature	From -40 to + 85°C
Hail Diameter @ 80km/h	Up to 25mm
Front Side Maximum Static Loading	5400Pa
Rear Side Maximum Static Loading	2400Pa
Maximum Series Fuse Rating	35A
PV Module Classification	II
Fire Rating (IEC 61730)	C
Maximum System Voltage	DC 1500V

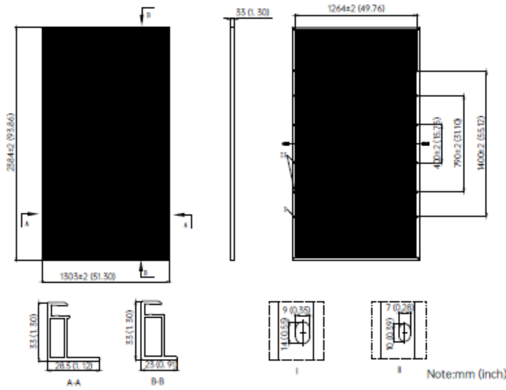
Packing Configuration

Container	40' HQ
Pieces/Container	594
Pcs/Pallet	33
Pallets/Container	18

Electrical Characteristics







Note:mm (inch)

PHONO

PHONO SOLAR TECHNOLOGY CO., LTD. reserves the right to make necessary adjustments to the information described herein at any time without further notice. The specifications and certificates contained in this datasheet may deviate slightly from our actual products due to the on-going innovation and product enhancement. Please be sure to use the most recent version of data.

APPENDIX 4. HUAWEİ INVERTER DATASHEETS

SUN2000-110KTL-M0
Technical Specifications

Efficiency	
Max. Efficiency	98.6%
Chinese Efficiency	98.1%
Input	
Max. Input Voltage	1,100 V
Max. Current per MPPT	26 A
Max. Short Circuit Current per MPPT	40 A
MPPT Operating Voltage Range]	200 V ~ 1,000 V
Rated Input Voltage	600 V
Number of Inputs	20
Number of MPP Trackers	10
Output	
Rated AC Active Power	110,000 W
Max. AC Apparent Power	121,000 VA
Max. AC Active Power (cosϕ=1)	121,000 W
Rated Output Voltage	3 × 220 V/380 V, 3 × 230 V/400 V, 3W+N+PE
Rated AC Grid Frequency	50 Hz
Rated Output Current	167.2A (380Vac) , 158.8A (400Vac)
Max. Output Current	185.7A (380Vac) , 176.4A (400Vac)
Adjustable Power Factor Range	0.8 超前 ... 0.8 滞后
Max. Total Harmonic Distortion	< 3%
Protection	
Input-side Disconnection Device	Yes
Anti-islanding Protection	Yes
AC Overcurrent Protection	Yes
DC Reverse-polarity Protection	Yes
PV-array String Fault Monitoring	Yes
DC Surge Arrester	Type II
AC Surge Arrester	Type II
DC Insulation Resistance Detection	Yes
Residual Current Monitoring Unit	Yes
Communication	
Display	LED Indicators, Bluetooth + APP
RS485	Yes
USB	Yes
MBUS	Yes
General	
Dimensions (W x H x D)	1,035 x 700 x 365 mm
Weight (with mounting plate))	85 kg
Operating Temperature Range	-25°C ~ 60°C
Cooling Method	Natural Convection
Max. Operating Altitude	5,000 m (> 4,000 m降额)
Relative Humidity	0 ~ 100%
DC Connector	Amphenol HH4
AC Connector	OT端子
Protection Degree	IP65
Topology	Transformerless

APPENDIX 5. MATLAB CODES

The MATLAB code evaluates photovoltaic panel performance, calculating annual energy production and cumulative income, considering 0.4% and 0.5% annual efficiency losses.

```
% Parameters
initial_energy_production = 929715; % kWh, first-year energy
production
electricity_price = 0.13412; % USD per kWh
annual_loss_rate = 0.004; % 0.4% annual degradation
years = 25; % Total years of operation
% Initialize arrays
year = (1:years)'; % Year array
energy_production = zeros(years, 1); % Energy production per year
annual_revenue = zeros(years, 1); % Revenue per year
cumulative_revenue = zeros(years, 1); % Cumulative revenue
annual_energy_loss = zeros(years, 1); % Annual energy loss
cumulative_energy_loss = zeros(years, 1); % Cumulative energy loss
% Initial conditions
current_energy = initial_energy_production;
total_revenue = 0;
total_loss = 0;
% Calculations for each year
for i = 1:years
 energy_production(i) = current_energy; % Current year's energy
production
 annual_revenue(i) = current_energy * electricity_price; % Revenue
for the year
 total_revenue = total_revenue + annual_revenue(i); % Update
cumulative revenue
 cumulative_revenue(i) = total_revenue; % Store cumulative revenue
 % Calculate energy loss
 annual_loss = initial_energy_production - current_energy;
 total_loss = total_loss + annual_loss; % Update cumulative loss
annual_energy_loss(i) = annual_loss; % Store annual loss
 cumulative_energy_loss(i) = total_loss; % Store cumulative loss
    % Update energy production for the next year
    current_energy = current_energy * (1 - annual_loss_rate);
end
```