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Article

Comparative evaluation of solar photovoltaic cell technologies across Türkiye's climatic regions: A PVsyst simulation-based analysis

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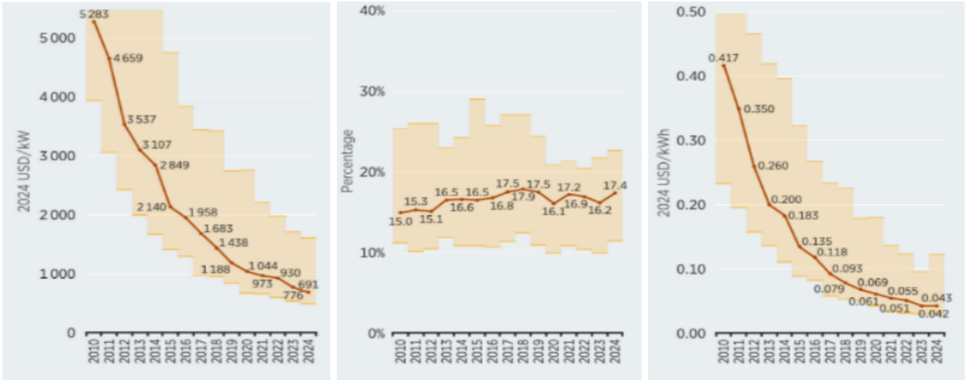
Abstract: Over the past fifteen years, solar photovoltaic (PV) technologies have become a part of the global energy transition, primarily driven by sustained reductions in capital costs. This rapid deployment has intensified the need for robust, technology-specific performance assessments under diverse climatic conditions. This study presents a comparative evaluation of three crystalline silicon PV cell technologies, which are Passivated Emitter and Rear Contact (PERC), Tunnel Oxide Passivated Contact (TOPCon), and Silicon Heterojunction (SHJ/HJT), across Türkiye's climatically heterogeneous regions using PVsyst simulation software. A rigorously controlled modelling framework was employed, in which all system-level parameters, including irradiance data, thermal behaviour, array configuration, and loss assumptions, were held constant across simulations, thereby isolating the impact of cell architecture on energy yield. The results demonstrate clear performance differentiation among the examined technologies. SHJ modules exhibit superior energy output under high temperature conditions due to favourable temperature coefficients, whereas TOPCon modules show enhanced robustness under harsh operating environments and improved resistance to lifetime degradation. PERC technology, despite its maturity, remains competitive in regions characterised by moderate climatic stress. These findings indicate that PV technology selection should extend beyond nominal efficiency metrics to incorporate thermal sensitivity, degradation behaviour, and low irradiance performance. Consequently, informed PV investment and deployment strategies must align cell technological attributes with specific environmental conditions. While controlled PVsyst simulations provide a consistent comparative baseline, their practical relevance depends on careful contextualisation to real-world operating environments.

Keywords: PV cell technology; renewable energy; PV cell performance; PVsyst; performance optimization

1. Introduction

Over the past fifteen years, solar energy has undergone a transformation, evolving into a major contributor to global electricity. Photovoltaic (PV) systems have advanced through coordinated progress in technology, economics, and policy frameworks. Continuous reductions in generation costs, as reported by IRENA (2024) [1], have coincided with rapid capacity expansion and sustained innovation. Crystalline silicon has emerged as the prevailing PV material, supported by advances in cell structures such as PERC, TOPCon, and silicon heterojunction designs, which have substantially elevated commercial module efficiencies. Parallel improvements in manufacturing processes and system integration have further accelerated cost reductions, positioning utility-scale solar power among the most economically competitive electricity generation options worldwide [1]. The trend of PV technology in terms of installed cost, capacity factor and levelized cost of electricity is given in **Figure 1**.



(a) **(b)** **(c)**

Figure 1. Global weighted average and range of **(a)** Total installed cost; **(b)** Capacity factor; **(c)** Levelized cost of electricity for utility-scale solar PV, 2010–2024 [1].

The global installed capacity of solar power has an exponential increase. In 2010, global solar PV capacity was approximately 40 GW. By the end of 2024, it surpassed more than 1000 GW, driven largely by policy incentives, cost competitiveness, and climate commitments. The largest contributions have come from China, the European Union, the United States, and, more recently, India and Southeast Asia. According to the IEA report, Solar Energy is expected to be an energy pioneer by the end of 2030 [2]. Foreseen energy outlook by 2030 is illustrated in **Figure 2**.

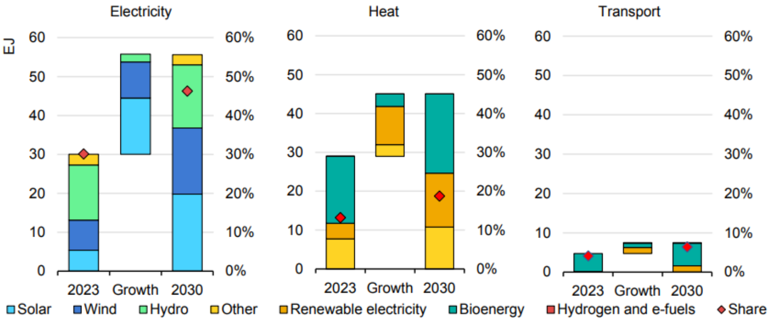


Figure 2. Foreseen energy outlook by 2030 [2].

The global diffusion of solar power has been enabled by supportive policy instruments, market mechanisms and technological maturation. Concurrent advances in PV cell architectures reflect distinct strategies to mitigate recombination losses while sustaining cost effectiveness and scale manufacturing [2]. The main structure of these PV cells is illustrated in **Figure 3** below [3].

According to the projections presented in the International Technology Roadmap for Photovoltaic (ITRPV), while PERC will gradually lose dominance, TOPCon is projected to emerge as the leading technology due to its higher efficiency potential and manufacturing compatibility, whereas SHJ adoption may remain constrained by cost and process complexity [4]. Market share expectation of PV cell technologies is given in **Figure 4**.

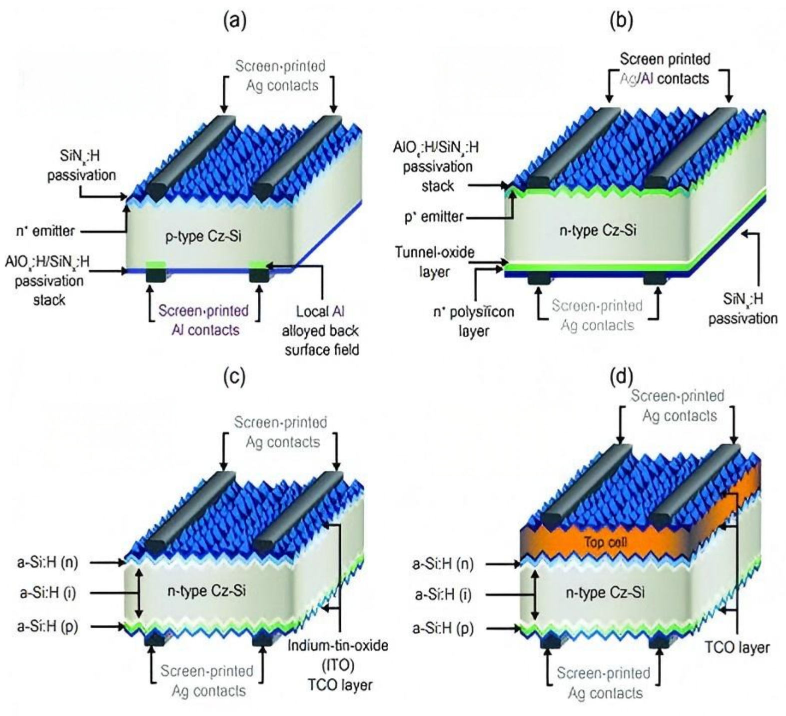


Figure 3. Illustrated structure of PV technologies: **(a)** PERC; **(b)** TOPCon; **(c)** SHJ; **(d)** Tandem [3].

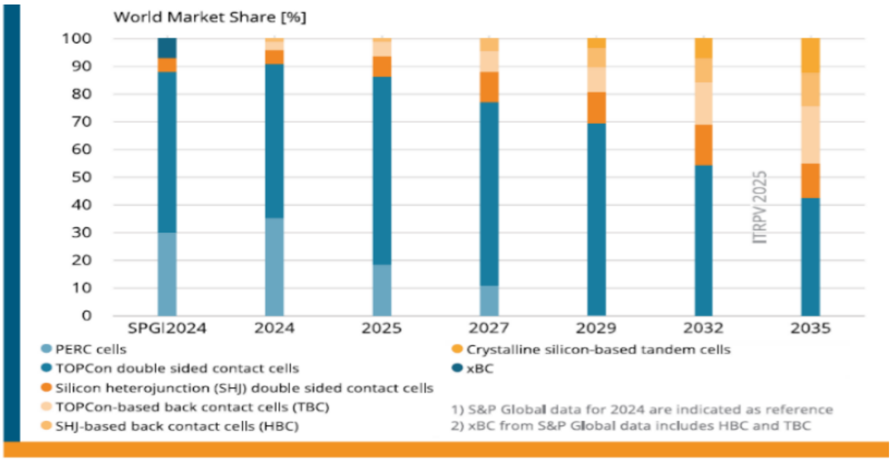


Figure 4. Market shares for different cell technologies from GW-scale manufacturers [4].

Despite substantial progress in photovoltaic deployment, challenges related to cell structure and ambient limitations remain.. PERC technology, while industrially mature, faces efficiency saturation and is increasingly affected by irradiation and degradation, constraining lifetime performance. TOPCon cells offer improved passivation but introduce challenges related to process complexity, contact resistivity, and cost scalability in mass production. Silicon heterojunction (SHJ) technologies achieve high efficiencies and favorable temperature coefficients; however, their reliance on low-temperature processing, indium-containing transparent conductive oxides, and tight manufacturing tolerances poses economic and supply chain constraints. The competitive landscape of PV technology is thus shifting toward high-efficiency architectures that can balance performance, reliability, and cost. As global demand for clean energy accelerates, continuous innovation in materials, processes, and device architecture will determine the leading technologies in the next generation of solar photovoltaics. A comparison matrix of these technologies is given in **Figure 5** [3,5].

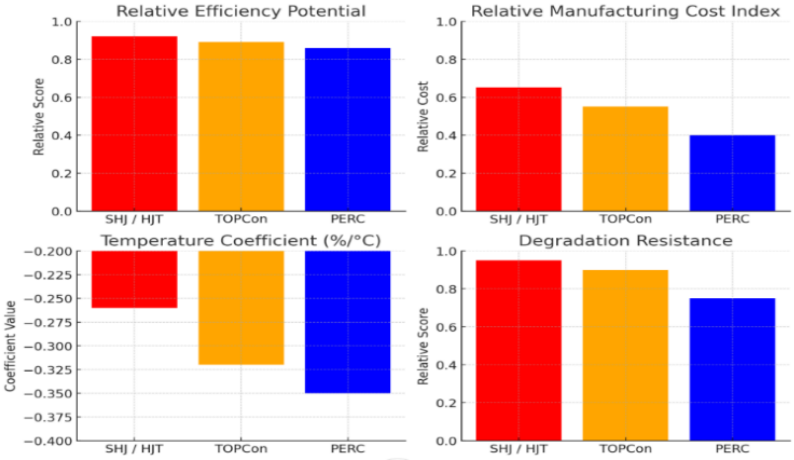


Figure 5. Comparison of PV cell technologies [3,5].

Kivambe et al. compared the performance of PERC, TOPCon, and SHJ PV modules operated for three years under Qatar's desert conditions, evaluating degradation rates, energy yields, and structural defects among other key parameters [5]. Zhou et al. proposed novel heterojunction architectures aimed at overcoming key technical limitations of PERC modules, which have emerged over the past decade as dominant players in the photovoltaic market [6]. Shen et al. conducted extensive investigations into mainstream approaches for enhancing solar cell efficiencies employed in photovoltaic modules [7]. Anderson et al. developed a comprehensive dataset by analyzing the parameters of fifteen distinct PV cell types intended for use within the PVsyst simulation software [8]. Chang et al. have provided a critical assessment of key materials employed in advanced photovoltaic technologies, particularly in PERC and TOPCon solar cells. Their analysis highlights material performance attributes, potential limitations, and implications for enhancing efficiency and durability [9]. Liu et al. emphasized that impedance spectroscopy enables the characterization of degradation processes in photovoltaic modules, offering valuable insights into performance decline. Their study further underscores its utility in comparing different PV cell types, thereby facilitating a deeper understanding of aging mechanisms and operational stability [10]. Xu et al. conducted research on photovoltaic panel performance, with a particular focus on TOPCon. Their study explored strategies to enhance efficiency, offering insights into technological optimizations and design improvements that can drive superior energy conversion in advanced PV architectures [11]. Liu et al. carried out investigations aimed at enhancing the performance of SHJ type photovoltaic panels. Their work focused on optimizing device architecture and material properties, thereby improving energy conversion efficiency and operational stability [12]. Li et al. investigated the influence of varying material thicknesses on UV resistance, with a specific focus on TOPCon photovoltaic cells. Their findings reveal critical correlations between layer configuration and lifetime durability, offering guidance for improving reliability in advanced PV Technologies [13]. Liang et al. provided a comprehensive overview of solar cell evolution from silicon based PV panels to SHJ type technologies, examining how mechanical and other structural properties influence performance. Their analysis highlights the interplay between design parameters and efficiency, offering valuable perspectives for advancing PV module engineering [14]. Leung et al. investigated the evolution of photovoltaic panel technologies alongside an assessment of circular economy principles. Their study emphasizes sustainable material use, end-of-life management, and recycling strategies, linking technological advancement with environmental and economic resilience in the solar energy sector [15]. Yuan et al. examined performance and energy efficiency losses in PERC cells. Their research identifies key degradation mechanisms, quantifies their impact on lifetime output, and provides insights into mitigating efficiency decline through material and process optimization [16]. Gao et al. investigated the effect of doped materials on the efficiency of silicon solar cells. Their study demonstrates how controlled doping strategies can modify electronic properties, enhance carrier transport, and ultimately improve energy conversion efficiency [17]. Li et al. conducted an investigation into lead (Pb) content across 96 photovoltaic samples, including PERC panels. Their analysis evaluates the presence and distribution of Pb, highlighting implications for environmental safety, regulatory compliance, and sustainable management in PV technologies [18]. Öz et al. explored the optimization of PV panel manufacturing processes, focusing on the development of low-temperature lamination techniques for Perovskite/Si tandem structures. Their work aims to enhance structural integrity and performance while ensuring compatibility [19]. Chen et al. discussed advancements and technological innovations in screen printing within PV solar cell manufacturing. Their review highlights improvements in printing precision, paste formulations, and process integration, contributing to higher efficiency, reduced material waste, and enhanced scalability in photovoltaic production [20]. Karade et al. investigated the potential of inorganic tandem solar cells, outlining their advantages alongside the challenges that must be addressed. Their study highlights prospects for high efficiency and stability while emphasizing the need to overcome material compatibility, fabrication complexity, and barriers [21]. Khokhar et al. emphasized that achieving p-type TOPCon solar cells requires meticulous process optimization. Their findings underline the critical role of refining fabrication parameters to maximize energy conversion efficiency and ensure consistent performance in advanced PV technologies [22]. Zhang et al. investigated the use of carbon films in the production of solar cells. Their research demonstrates how carbon-based layers can enhance conductivity, and stability, offering a promising pathway for photovoltaic device engineering [23]. Wang et al. examined the impact of doping processes on the performance and efficiency of TOPCon solar cells. Their study reveals how optimized dopant selection and concentration can improve carrier lifetime, reduce recombination losses, and enhance overall energy conversion in advanced PV architectures [24]. Pirot-Berson et al. investigated the influence of structural layers on SHJ-type solar cells. Their research highlights how variations in layer composition, thickness, and interface quality affect carrier transport, recombination dynamics, and overall device efficiency in photovoltaic systems [25]. Nasser et al. investigated the structural properties of PERC-type solar cells. Their study examines how layer configuration, material quality, and interface characteristics influence carrier dynamics and overall device performance, providing insights for optimizing efficiency and durability in advanced PV systems [26]. Jang et al. explored loss mechanisms and layer engineering in perovskite/Si tandem solar cells. Their research identifies critical factors affecting energy conversion efficiency and demonstrates how tailored layer design can mitigate losses, enhance carrier management, and optimize performance in photovoltaic devices [27]. Jäger et al. highlighted photovoltaic technology as a key instrument for achieving decarbonization, emphasizing its strategic role in the energy transition. Their assessment focuses on deployments, evaluating their potential to deliver substantial carbon reductions while supporting sustainable energy generation [28]. Brecl et al. investigated the performance of bifacial PV systems. Their study evaluates how varying irradiance components impact energy yield, providing a framework for more accurate performance prediction and optimization of bifacial photovoltaic installations [29]. ChenLi et al. examined the degradation reactions of TOPCon solar cells in acidic environments. Their investigation reveals the chemical and structural changes induced by acid exposure, offering insights into durability challenges and strategies for enhancing corrosion resistance in advanced PV technologies [30]. Du et al. conducted applications specifically on TOPCon type solar cells, analyzing their effects on performance and efficiency. Their findings demonstrate how targeted modifications in cell design and processing can enhance energy conversion, reduce losses, and improve operational stability in advanced photovoltaic systems [31]. Su et al. investigated silicon heterojunction solar cells, focusing on their energy conversion characteristics. Their research highlights the design advantages of solar architectures, demonstrating improved carrier collection, reduced recombination losses, and enhanced overall efficiency in photovoltaic applications [32]. Banerjee et al. investigated the structural properties of PERC-type solar cells, examining their influence on energy conversion efficiency. Their study identifies key design and material factors that affect performance, offering strategies to optimize structure for enhanced photovoltaic output [33]. Cao et al. examined the impact of back contacts on the efficiency of photovoltaic cells. Their research analyzes how contact design, material selection, and interface quality influence carrier transport and recombination, ultimately affecting overall energy conversion performance [34]. Kirchartz et al. studied the transition of PV solar cell efficiency from prototypes to commercial production. Their work addresses the performance gap, identifying factors such as material uniformity, process scalability, and defect control as critical to maintaining high efficiency in mass manufacturing [35]. Huang et al. conducted research on SHJ-type solar cells, which have recently emerged as one of the most advanced cell architectures. Their study explores material optimization, interface engineering, and fabrication techniques aimed at maximizing efficiency and operational stability [36]. Xu et al. examined the influence of individual layers on the efficiency of TOPCon solar cells. Their research highlights how variations in thickness, material properties, and interface quality can significantly impact carrier dynamics, recombination behavior, and overall energy conversion performance [37].

Hudişteanu et al. examined the influence of operating temperature on photovoltaic panel performance. This study experimentally investigates monocrystalline and polycrystalline panels of identical nominal power (30 Wp) using a climatic chamber and solar simulator. Elevated temperatures notably reduce open circuit voltage, power output, and conversion efficiency, while cooling the panel's backside enhances performance. Results indicate a temperature coefficient of efficiency around −0.52%/°C and demonstrate differences between panel types due to material and spectral response. The findings underscore the potential of temperature management to optimize PV efficiency, supporting sustainable energy integration in building applications [38]. Karafil et al. stated PV panels convert solar energy directly into electrical energy through semiconductor materials. Panel performance is influenced by multiple factors, including tilt angle, shading, dust, wiring losses, solar radiation, and temperature, with the latter two being particularly significant. Solar radiation varies by panel location and time of day, directly affecting power output, whereas ambient temperature exhibits an inverse relationship with panel power. This study simulated the PV panel equivalent circuit in PSIM and MATLAB using catalogue data to investigate the effects of temperature and solar irradiance panel performance [39]. Wang et al. examined how solar spectral irradiance distributions (SIDs) critically influence on the photoelectric conversion performance of photovoltaic materials. This study evaluated the practical conversion efficiency of ten PV materials in Beijing and Changsha, China, using average photon energy. Photon energy utilization efficiency is proposed to compare performance across materials with identical aperture areas. Monocrystalline silicon performs best under reference spectra, whereas gallium arsenide excels when average photon energy exceeds 1.95 eV. Perovskite materials show variable mismatch factors depending on bandgap and spectral conditions. The study further proposes an ideal PV material optimized for regional SIDs, offering guidance for tailoring PV technologies to local solar spectra [40]. Bevanda et al. stated spectral irradiance is crucial for optimizing photovoltaic system performance. This study evaluated eight PV technologies across 79 European sites using satellite sky conditions. Results reveal systematic blue shifts in real spectra, with only 2–5% resembling AM1.5 reference conditions. Thin film technologies exhibit substantial spectral gains under blue-shifted spectra, whereas crystalline silicon variants maintain high stability (<1.6%). Latitude-dependent effects are influenced by air mass, water vapor, and aerosol content. The findings highlight the necessity of site spectral assessments to maximize energy yield and inform technology selection for diverse climates [41].

2. Materials and methods

In this study, PVsyst is employed as a robust energy yield calculation tool. Its advanced hourly simulation framework enables detailed modelling of thermal behaviour, system losses, shading, and component interactions. Owing to its validated databases and analytical depth, PVsyst constitutes a reliable platform for rigorous photovoltaic performance assessment. The selected provinces' map of case is given in **Figure 6**.

PVsyst simulations were conducted in Türkiye to estimate the electricity generation of PERC, TOPCon, and SHJ photovoltaic cell technologies across provinces representing distinct climatic and geographical conditions. The selected cities, chosen for their characteristic environmental features, are illustrated on the Turkish Solar Energy Potential Atlas, underscoring their relevance for comparative photovoltaic performance assessment.

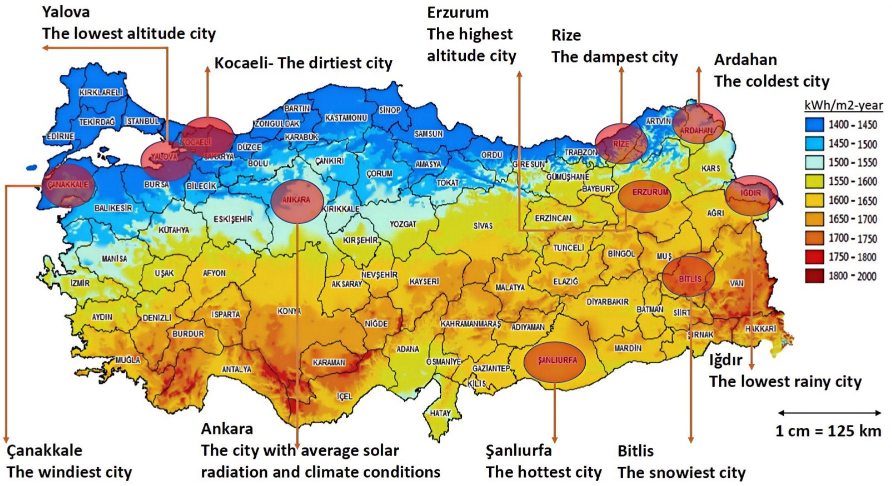


Figure 6. Selected provinces for PVsyst study case.

Ankara represents a semiarid continental climate typical of Central Anatolia. Ardahan and Erzurum exhibit severe high altitude continental climates, while Bitlis reflects eastern highland conditions with pronounced winter snowfall. Iğdır constitutes a low altitude microclimate within Eastern Anatolia, characterized by hotter summers and reduced precipitation. Çanakkale experiences a transitional Mediterranean/Marmara climate influenced by maritime effects. Kocaeli (Gebze) and Yalova represent humid Marmara climates with moderate seasonal variability. Rize exemplifies the humid Black Sea climate with persistent precipitation, whereas Şanlıurfa displays a hot semiarid climate marked by extreme summer temperatures and strong seasonal aridity. Key climatic parameters and altitudes are summarized in **Table 1**.

Table 1. Climatic parameter summary with altitudes.

Province	Climate type	Annual P.(mm)	Temp range (°C)	Altitude (m)	Notable features
Ankara	Semi-arid continental	350–400	−5 to 32	~938	Dry summers, spring rainfall peak
Ardahan	High-altitude continental	500–600	−20 to 25	~1800	Long, snowy winters
Erzurum	High-altitude continental	450–550	−20 to 26	~1900	Harsh winters, short mild summers
Bitlis	Mountain continental	800–1200	−10 to 27	~1540	Heavy winter snowfall
Çanakkale	Transitional Mediterranean–Marmara	600–700	5 to 30	~5	Maritime moderation
Kocaeli	Humid Marmara	700–900	4 to 30	~130	Even precipitation distribution
Iğdır	Semi-arid lowland continental	250–350	−5 to 35	~850	Mild winters for Eastern Anatolia
Rize	Humid subtropical (Black Sea)	2000–2500	7 to 28	~6	Year-round rainfall, orographic enhancement
Şanlıurfa	Hot-summer semi-arid	350–450	5 to 42	~518	Extreme summer heat, winter rainfall concentration
Yalova	Humid Marmara	800–1000	6 to 30	~2	Mild winters, warm summers

It clearly visualizes how provinces like Erzurum and Ardahan sit at the highest elevations, while Rize combines low altitude with extremely high precipitation, illustrating the strong maritime influence of the Black Sea. Iğdır remains low in precipitation despite its moderate altitude, reflecting its enclosed basin microclimate. The completed climate zone clustering chart showing the selected provinces positioned by altitude and annual precipitation, with colour coding for their respective climate types, is shown in **Figure 7**.

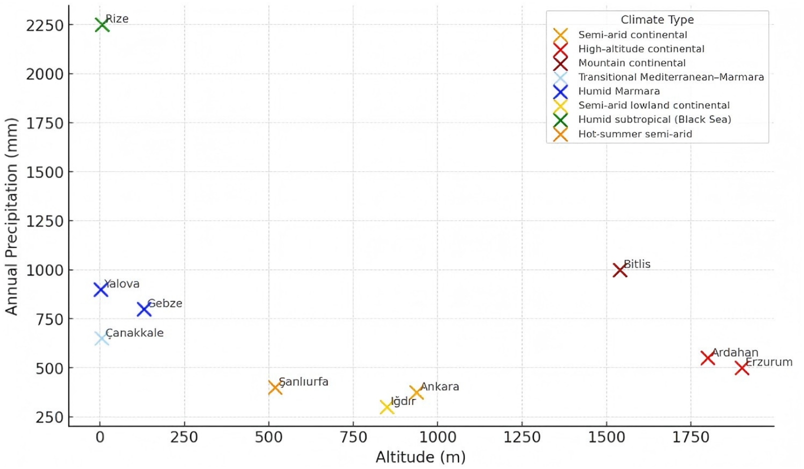


Figure 7. Climate zone clustering by altitude and precipitation.

Recent advancements in PV module manufacturing have resulted in diverse technological approaches, each optimized for specific performance, cost, and durability objectives. Among notable industry examples, Huasun Solar's DS585, JinkoSolar's JKM-585N-72HL4-BDV, and JinkoSolar's JKM585M-7RL4-V represent three distinct design philosophies: SHJ/HJT, TOPCon, and P-Type Monocrystalline PERC, respectively. Also, technical parameters of these cells are embedded in the PVsyst software program.

- Huasun Solar DS585: This model integrates SHJ cell architecture, which combines crystalline silicon wafers with thin amorphous silicon layers. The design aims to minimize recombination losses, enhance bifaciality, and maintain superior temperature coefficients. Its n type base structure provides immunity to light induced degradation (LID).
- JinkoSolar JKM-585N-72HL4-BDV: Employing n-type TOPCon technology, this module focuses on achieving high conversion efficiencies through advanced passivation and optimized carrier transport. TOPCon cells typically exhibit improved performance under low irradiance, superior bifacial gains, and better degradation resistance compared to standard PERC designs.
- JinkoSolar JKM585M-7RL4-V: This model uses p type monocrystalline cells, typically associated with PERC enhancements. While more mature and cost-efficient to manufacture, p-type cells are more susceptible to LID and have slightly lower efficiency ceilings compared to n type technologies. However, they remain a reliable choice for projects prioritizing proven performance and lower upfront costs [3,5,6]. A technical feature comparison of cells is given in **Table 2**.

Table 2. Technical feature comparison.

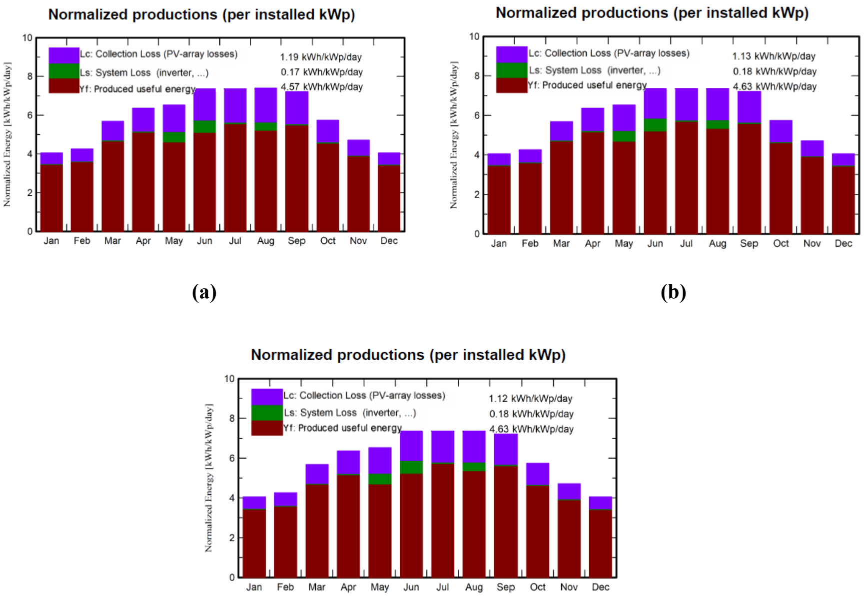
Model	**Cell type**	**Base wafer type**	**Technology**	**Potential limitations**
Huasun Solar DS585	SHJ/HJT	N-Type	Heterojunction	Higher manufacturing complexity and cost
JinkoSolar JKM-585N-72HL4-BDV	TOPCon	N-Type	Passivating Contact	Slightly higher cost than PERC; emerging large-scale manufacturing base
JinkoSolar JKM585M-7RL4-V	P-Type Monocrystalline (PERC)	P-Type	Passivated Emitter and Rear Cell	Light-induced degradation (LID) risk, lower efficiency potential than n-type

3. Results and discussion

The assumptions adopted in this study are as follows:

- For the PERC cell type, the JinkoSolar JKM585M-7RL4-V PV module was used; for the TOPCon cell type, the JinkoSolar JKM-585N-72HL4-BDV PV module was employed; and for the SHJ cell type, the Huasun Solar DS585 PV module was selected.
- Calculations were performed for the ten previously specified cities.
- In PVsyst, the technical parameters of the aforementioned PV cell types are embedded within the software's database.
- All simulations were conducted assuming an installed capacity of 1 MW.
- The nominal PV module power was set at 585 W for all three cell types.
- A Huawei inverter with a nominal capacity of 200 kW was used in all cases.
- In PVsyst, only the PV cell type was varied to determine the resulting energy output; all other parameters and site-specific conditions for each location were kept constant, in line with the ceteris paribus assumption.

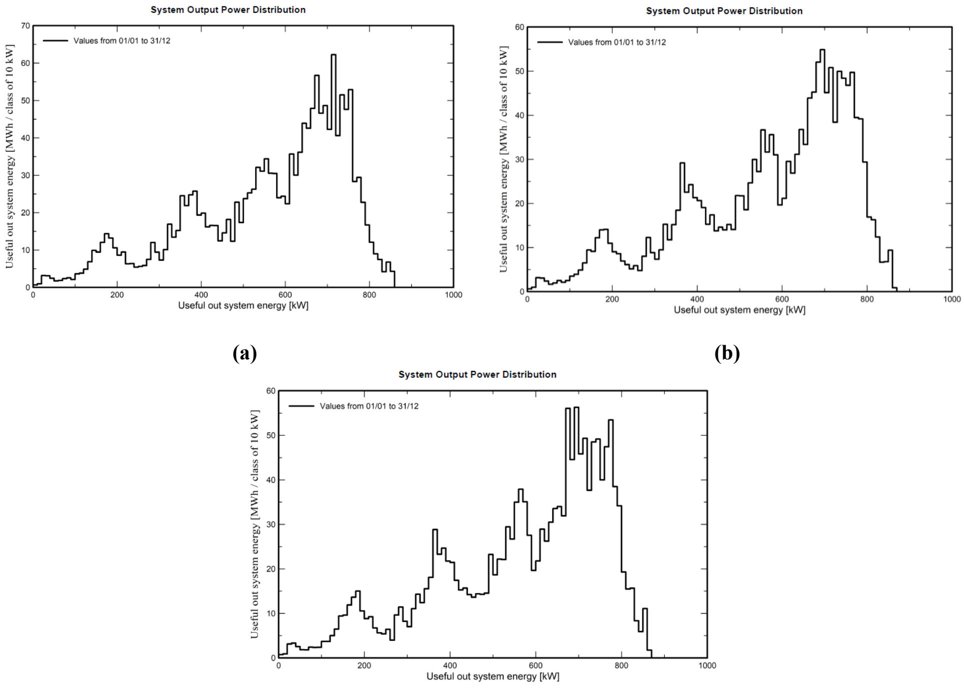
A detailed sample of PVsyst result is given in **Figures 8–11** for Şanlıurfa province.



(a) **(b)**

(c)

Figure 8. System generation results for Şanlıurfa province: **(a)** PERC; **(b)** TOPCon; **(c)** SHJ.

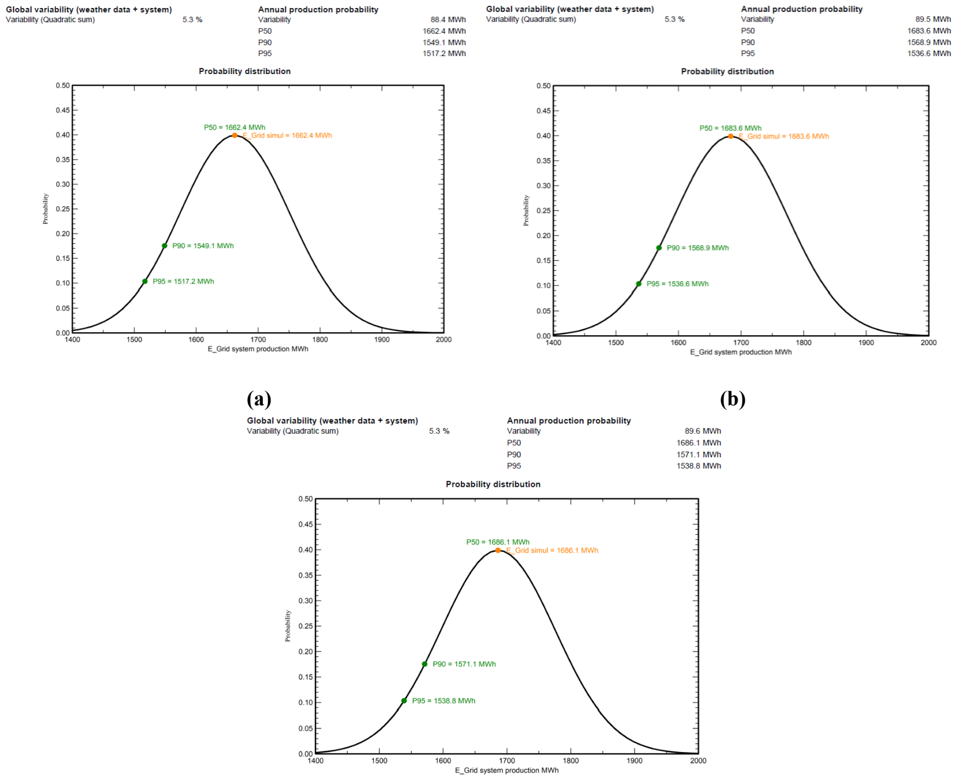


(a)

(b)

(c)

Figure 9. System output power distribution for Şanlıurfa province: **(a)** PERC; **(b)** TOPCon; **(c)** SHJ.



(a)

(b)

(c)

Figure 10. Probability distribution for Şanlıurfa province: **(a)** PERC; **(b)** TOPCon; **(c)** SHJ.

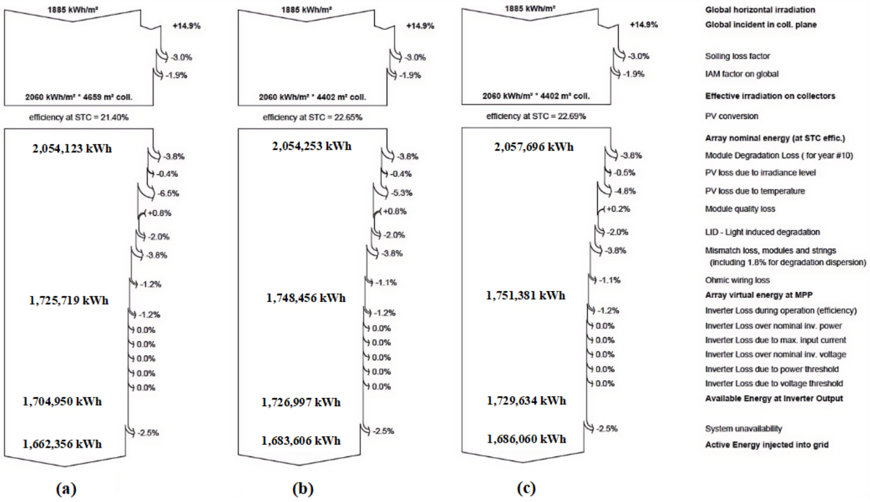


Figure 11. Loss diagram of systems: **(a)** PERC; **(b)** TOPCon; **(c)** SHJ.

The following **Table 3** presents recorded annual PV production (MWh) by technology across select Turkish provinces, each uniquely defined by a climate characteristic.

Table 3. A summary of the PVsyst study.

Province	Climate feature	PERC (MWh)	TOPCon (MWh)	SHJ (MWh)
Ankara	Moderate continental	1567.2	1577.5	1576.0
Ardahan	Coldest winters (high elevation)	1636.4	1639.3	1634.4
Bitlis	Snowiest, mountainous	1766.3	1775.7	1773.2
Çanakkale	Windy coastal terrain	1462.5	1473.9	1473.0
Kocaeli	High air pollution	1274.1	1283.3	1282.6
Iğdır	Low precipitation, dry basin	1322.1	1332.3	1331.6
Rize	Wettest, humid	1369.3	1377.5	1375.6
Şanlıurfa	Hottest summer region	1662.4	1683.6	1686.1
Yalova	Lowest elevation, coastal	1304.5	1293.5	1304.5
Erzurum	Highest elevation, frigid winters	1789.9	1795.3	1791.0

According to the PVsyst result:

- SHJ modules consistently lead in conversion efficiency (lab scale ~26.8%) thanks to superior surface passivation and high open-circuit voltage [5]. SHJ exhibits superior thermal resilience (temperature coefficient ~0.23%/°C), maintaining performance in high temperature environments [42,43]. SHJ modules suffered up to high performance loss over three years, largely due to encapsulant degradation and delamination. SHJ is ideal where efficiency peaks matter, high irradiance sites (e.g., Şanlıurfa).
- TOPCon follows closely with ~26% efficiency, enhanced carrier selectivity, and low degradation properties. TOPCon shows moderate temperature sensitivity, outperforming PERC in hot climates. TOPCon demonstrated remarkable reliability; one module endured only relatively low degradation. TOPCon is a resilient all-rounder excelling in high elevation, high humidity, windy, or polluted environments due to superior temperature stability and lifetime durability.
- PERC modules, while more affordable and widely deployed, retain comparatively

lower efficiency (~23.3%). PERC is most affected by heat, with higher performance decay in hotter conditions. PERC experienced high initial degradation that later stabilized. An effective baseline option for stable, moderate climates or low-budget scenarios, though with lower yield potential under stress.

A heatmap diagram is given in **Figure 12** for PVsyst results.

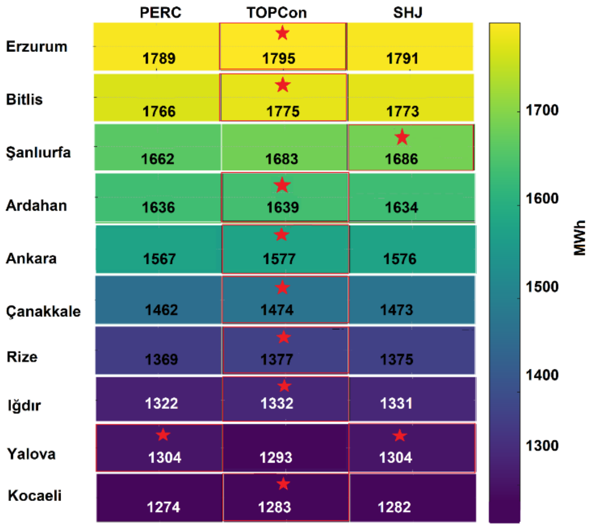


Figure 12. Heatmap diagram of PVsyst results.
Note: The red starred entries indicate the maximum values observed within each row.

Türkiye's abundant solar resource makes large scale PV deployment strategically compelling, yet climate sensitive technology choice is decisive. Rising heat and extremes increasingly constrain performance. Aligning SHJ with hot, high irradiance regions, TOPCon with harsh or variable climates, and PERC with stable zones maximizes energy yield, resilience, and long term system reliability nationwide sustainably. A summary is given in **Table 4.**

Table 4. A summary of PV technology-climate fit.

Technology	**Key strengths**	**Ideal climate fit(s)**
TOPCon	High efficiency, lowest degradation in harsh climates, moderate temp sensitivity	High-altitude, humid, dusty, coastal, snowy (most provinces)
SHJ (HJT)	Highest efficiency, best thermal coefficient	Hot climates (e.g., Şanlıurfa) despite degradation risk
PERC	Most cost-effective, mature technology	Moderate climates (e.g., Yalova) under lower stress

4. Discussion

Photovoltaic electricity generation in Türkiye displays pronounced spatial heterogeneity, reflecting the combined influence of solar availability and region's climatic conditions. An assessment of provinces including Kocaeli, Yalova, Iğdır, Rize, Çanakkale, Ankara, Ardahan, Şanlıurfa, Bitlis, and Erzurum demonstrates that cumulative PV output is governed by the interaction of altitude, ambient temperature, humidity, air quality, and irradiance. Provinces such as Kocaeli and Yalova exhibit the lowest total production, consistent with the adverse effects of dense industrial aerosols and low elevation, both of which are known to suppress effective solar irradiance and module performance.

Erzurum records the highest production levels, attributable to its high altitude and cool thermal regime. Reduced operating temperatures at elevated sites are widely reported to enhance PV efficiency, in some cases exceeding 40% gains relative to lowland, warmer environments. Provinces characterized by high humidity and frequent precipitation, notably Rize and Bitlis, achieve intermediate to high production levels. Although atmospheric moisture can attenuate incoming radiation and increase module temperatures, adequate solar availability compensates for these losses, sustaining robust generation.

Thermal conditions emerge as a critical determinant of technology performance. In Şanlıurfa, where irradiance is intense but ambient temperatures are elevated, PERC modules deliver slightly lower outputs than TOPCon and SHJ technologies. This pattern reflects the higher temperature coefficient and thermal sensitivity of PERC architectures. Similar constraints are observed in industrialized urban settings such as Kocaeli, where particulate pollution reduces optical transmittance and further limits yield.

Provincial PV performance in Türkiye is shaped by a convergence of climatic drivers. Cooler, high altitude environments favor technologies with strong thermal tolerance, while humid regions benefit from maintenance strategies that mitigate moisture and soiling losses. High irradiance zones consistently outperform others, yet only when thermal and atmospheric effects are adequately managed. These findings indicate that maximizing PV yield in Türkiye requires climate fit technology selection and region's operational strategies, rather than reliance on solar resource magnitude alone.

5. Conclusion

A comparative evaluation of photovoltaic electricity generation across Turkish provinces, conducted for PERC, TOPCon, and SHJ (HJT) cell architectures, provides a structured perspective on the interaction between climate, technology choice, and modeling methodology in energy system assessment. All yield estimates were derived using PVsyst, a widely established platform for PV system design and performance prediction. To ensure methodological rigor, irradiance datasets, meteorological inputs, thermal formulations, shading assumptions, and loss factors were maintained identically across simulations; the PV cell technology constituted the sole variable. This ceteris paribus framework enables a transparent comparison of technology fit behavior, independent of confounding parameter shifts, while acknowledging that variability may exceed what numerical models can fully resolve.

PVsyst employs advanced physical representations, including one-diode electrical models, cell temperature formulations, and standardized meteorological databases such as Meteonorm and PVGIS, to generate internally consistent and reproducible outputs. Within this controlled environment, provinces at higher elevation and with cooler ambient conditions, notably Erzurum, consistently achieve the highest simulated production across all module categories. In contrast, low altitude or industrialized provinces such as Kocaeli and Yalova exhibit the lowest yields, reflecting the well documented effects of elevated module temperatures, atmospheric pollution, and soiling on PV performance.

Despite the internal consistency of these simulations, deviations are expected under operational conditions. Factors such as long term degradation, dust accumulation, ultraviolet exposure, and localized microclimatic dynamics introduce uncertainties that are only partially captured by numerical tools. Even so, PVsyst's modeling framework offers a reliable comparative baseline, particularly valuable during early stage feasibility analysis, where relative performance trends are more critical than absolute yield values.

The results highlight the necessity of aligning PV technology characteristics with regional climatic conditions in procurement and investment decisions. In high temperature environments such as Şanlıurfa, SHJ modules, distinguished by low temperature coefficients and enhanced thermal stability, display a relative performance advantage over thermally sensitive PERC designs. In humid or snow affected regions, including Rize and Bitlis, technologies exhibiting strong low irradiance response and resilience to soiling, often SHJ or well passivated TOPCon variants, are more likely to sustain superior output in practice. Consequently, module selection should extend beyond nominal efficiency or cost considerations to incorporate the interaction between cell physics and local climate.

The ceteris paribus simulations conducted in PVsyst establish an essential reference under equalized conditions, enabling objective technology comparison. Final system design and technology choice, however, must be refined using site's parameters encompassing irradiance regimes, temperature distributions, altitude, soiling intensity, and maintenance strategies. Integrating high-fidelity simulation outcomes with regional climatic intelligence ultimately supports more reliable, resilient, and economically robust photovoltaic deployments across Türkiye's diverse geographic landscape.

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