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Türkiye'de Fotovoltaik Sistemlerin Fizibilitesinin Değerlendirilmesi: On-Grid, Off-Grid ve Şebeke Ölçekli FV Kurulumlarının Teknik ve Ekonomik Analizi

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ÖZET

Günümüz enerji üretiminin vazgeçilmezi olan fosil yakıtlar, sera gazı emisyonlarını açığa çıkararak önemli çevresel sorunlara neden olmaktadır. Daha temiz ve sürdürülebilir bir alternatif olarak, yenilenebilir enerji kaynakları, özellikle güneş enerjisi, dünya çapında önem kazanmıştır. Özellikle fotovoltaik (FV) sistemler, herhangi bir zararlı yan ürün olmadan elektrik üretmek için güneş enerjisinden yararlanmanın etkili bir yoludur. Bu teknoloji, Türkiye gibi büyük ölçüde fosil yakıtlara bağımlı ve zengin güneş enerjisi potansiyeline sahip ülkeler için büyük umut vaat etmektedir. Bu nedenle, bu çalışma Türkiye'deki FV sistemlerinin fizibilitesini değerlendirmeyi ve potansiyel engelleri keşfetmeyi amaçlamaktadır. Güvenilir ve sürdürülebilir enerji tedariki sağlamak için hem şebekeye bağlı hem de şebekeden bağımsız FV sistemleri dikkate alınır. Bu çalışmada değerlendirme, Türkiye'de farklı coğrafi bölgeleri temsil eden 7 il seçilerek yapılmıştır. Fotovoltaik sistemlerin teknik ve ekonomik fizibilite analizleri için Ulusal Yenilenebilir Enerji Laboratuvarı (NREL) tarafından geliştirilen Sistem Danışmanı Modeli (SAM) kullanılmıştır. SAM simülasyonu, güneş enerjisini kullanan bölgesel konut enerji taleplerini karşılamak üzere tasarlanmış şebeke dışı fotovoltaik sistemlere odaklanarak elektrik üretimi, verimlilik ve kayıplar dahil olmak üzere önemli teknik bilgiler sağlar. Bu çalışmada, İndirgenmiş Enerji Maliyeti (LCOE), İndirgenmiş Depolama Maliyeti (LCOS) ve paranın Net Bugünkü Değeri (NPV) gibi finansal parametreleri göz önünde bulundurarak şebekeden bağımsız FV sistemlerinin ekonomik uygulanabilirliği de araştırılmıştır. Bunlara ek olarak, seçilen şehirler için FV elektrik üretiminin şebeke elektriği ile maliyet açısından rekabet edebilir hale geldiğini gösteren şebeke paritesi kavramı da araştırılmıştır. Bu çalışma, fosil yakıt bazlı elektrik üretimine çekici bir alternatif olarak fotovoltaik sistemleri teşvik eden değerli bilgiler sunmaktadır.

Assessing the Feasibility of Photovoltaic Systems in Türkiye: Technical and Economic Analysis of On-Grid, Off-Grid, and Utility-Scale PV Installations

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ABSTRACT

Fossil fuels, whereas indispensable for energy production today, pose significant environmental challenges because of their greenhouse gas emissions. As a cleaner and sustainable alternative, renewable energy sources, particularly solar energy, have gained prominence worldwide. Photovoltaic (PV) systems offer an effective means of harnessing solar energy to generate electricity without harmful by-products. This technology holds great promise, especially for countries such as Türkiye, which heavily rely on fossil fuels and possess abundant solar energy potential. Thus, this study aims to assess the feasibility of PV systems in Türkiye and explore potential obstacles. To ensure a reliable and sustainable energy supply, both on-grid and off-grid PV systems are considered. The assessment was conducted by selecting 7 provinces that represent diverse geographical regions in Türkiye. The System Advisor Model (SAM), developed by the National Renewable Energy Laboratory (NREL), was employed for the technical and economic feasibility analyses of these PV systems. The SAM simulation provides crucial technical insights, including electricity production, efficiency, and losses, with a specific focus on off-grid PV systems designed to meet regional residential energy demands utilizing solar energy. Furthermore, this study investigates the economic viability of off-grid PV systems by considering factors such as the levelized cost of energy (LCOE), levelized cost of storage (LCOS), and the net present value (NPV) of money. In addition, the concept of grid parity, which indicates when PV electricity generation becomes cost-competitive with grid electricity, is explored for the selected cities, thereby promoting PV systems as an attractive alternative to fossil fuel-based electricity generation.

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INTRODUCTION

Energy has been a critical requirement for humanity throughout history. The Industrial Revolution marked the use of fossil fuels such as coal, oil, and natural gas, sustaining economies and improving living standards worldwide. However, these finite resources are rapidly depleting and pose significant environmental and ecological challenges [1]. In response to the unequal distribution and unsustainability of fossil fuels, countries are increasingly turning to renewable energy sources. Advancements in technology and escalating energy demands have accelerated this transition. Consequently, nations are taking significant strides toward diversifying their energy mix and embracing alternative sources, paving the way for renewable energy adoption. Renewable energy is derived from sources that are continuously or repeatedly replenished using natural processes. These energy sources offer a sustainable and eco-friendly alternative for various applications [2–4].

Over the last decade, the energy sector has witnessed a remarkable 130% increase in renewable energy capacity. By 2021, the total installed capacity of renewable electricity will surpass 3,064 GW, with approximately 8,000 terawatt-hours (TWh) of electricity produced from renewable sources. Among these technologies, photovoltaic (PV) systems have shown the highest growth, boasting a total installed capacity exceeding 843 GW [5], [6]. The growing interest in solar energy stems from its constant availability and its environmentally friendly nature. As a clean energy source, photovoltaic systems have gained prominence and are widely preferred in the renewable energy market [7]. PV technology harnesses photon energy from the sun and directly converts it into electrical energy without generating any polluting gasses. The reduction of carbon dioxide emissions and the sustainability of PV technologies have contributed to their widespread adoption. Solar energy has now become a well-established alternative energy source.

Given the diverse energy sources available, Türkiye stands out with its high solar energy potential. Despite not being rich in fossil resources, Türkiye boasts an average annual sunshine duration of 2,741 h and a total radiation value of 1,527.46 kWh/m². This abundant solar energy potential alone can sufficiently meet a country's energy needs [8]. As of December 2022, Türkiye's total installed electricity generation capacity reached 103.8 GW, with solar PV electricity generation accounting for only 9.1% of the total installed capacity [9]. Despite this potential, Türkiye has not fully tapped into its solar energy resources. The primary challenge lies in the installation costs of power plants and the overall cost of electricity production. In PV systems, this is determined by the levelized cost of energy (LCOE), which measures the actual cost of energy produced in USD/kWh. Numerous design decisions influence the LCOE [10]. Installation costs of PV systems vary across regions because of differences in solar radiation, financing conditions, and electricity prices [11]. The key reason for PV systems' preference is their ability to produce power at an LCOE equal to or lower than the price of purchasing electricity from the grid. This study aims to thoroughly examine the necessary infrastructure, potential support, and challenges involved in generating alternative energy using PV systems in different geographical regions of Türkiye.

TECHNICAL VARIABLE OF SIMULATION

System Advisor Model

Various simulation programmes are available for designing and analysing PV systems. Among them, the System Advisor Model (SAM) developed by the National Renewable Energy Laboratory (NREL) in 2007 [12] was employed for designing rooftop on-grid, rooftop off-grid, and commercial utility-scale PV systems in this study.

In the simulated systems, the on-grid PV systems are designed to consume the generated electricity on-site. On the other hand, the off-grid systems are equipped with batteries, which necessitates a change in methodology to either front-of-meter (FOM) or behind-meter (BTM) strategies. For utility-scale PV systems, the focus is on producing electricity at levels that are either lower or equal to the electricity price of the region, while also assessing the feasibility and profitability of potential investments.

To comprehensively understand Türkiye's PV system potential, we selected seven cities located in different geographical regions: Artvin, Bingöl, Karaman, Sanliurfa, Tekirdag, Trabzon, and Yozgat. The selection of these cities falls within a range representing Türkiye's wide geographical and climatic diversity. This diversity allows each city to have its unique energy dynamics. While the northern provinces, Artvin and Trabzon, draw attention with their heavy rainfall, Sanliurfa in the south stands out with its high sunshine hours. Different climatic conditions vary the performance of solar energy systems. In addition, the different energy demands in each city provide unique opportunities for solar energy projects. Bringing together developed cities and developing regions offers a comprehensive perspective of economic and social diversity. Within this framework, the potential of our chosen cities for solar energy systems is notable not only in terms of energy production but also for their positive impact on the local economy and community structures.

The data used in the SAM simulation programme were acquired from real measured values and reliable databases from national and international sources. The simulation methodology remained consistent across all cities, except for location-specific parameters such as irradiance data, system size, battery capacity, and financial inputs, which were tailored to each city's characteristics.

Locations and Weather

Any location that receives sunlight has the potential for solar energy generation. Solar radiation, which indicates the incident solar energy on an object, serves as a key metric in assessing the viability of an installed PV system. The selection of cities for this study considered both solar potential and electricity consumption values. Table 1 provides a list of the selected cities along with their current global horizontal irradiance (GHI), average temperature, and wind speed.

Hourly solar radiation data for the selected locations were sourced from five different databases, including the National Solar Radiation Database (NSRDB) [13], Photovoltaic Geographic Information System (PVGIS) [14], Climate One Building Organization [15], Global Solar Atlas [16], and Energy Plus [17]. Recognizing that data from different sources may introduce uncertainties in future forecasting, a four-fold series of methods, comprising single and double exponential smoothing (SES and DES, respectively), and simple and double moving averages (SMA and DMA, respectively), were used to process each hour of data. The annual average temperature and wind speed, which significantly impact the performance of solar panels, are also included in Table 1.

Considering this comprehensive dataset, the selected cities are categorized into three groups:

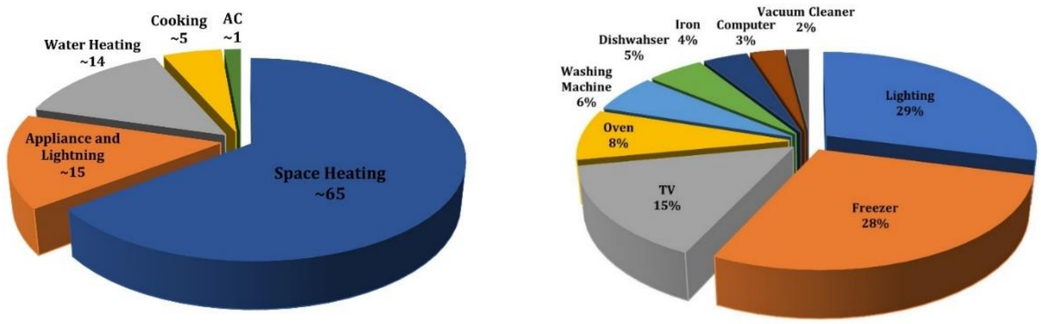
- High Zone Cities: These exhibit insolation values exceeding 5 kWh/m².
- Middle Zone Cities: Falling within the range of insolation values between 4 kWh/m² and 5 kWh/m².
- Lower Zone Cities: Encompassing cities with insolation values below 4 kWh/m².

Energy Demand and Electric Load

Following the selection of cities and the evaluation of solar radiation, the electrical load of households was determined. The average energy consumption of a household encompasses electricity usage for household appliances, lighting, water heating, cooking, and air conditioning. The distribution of these components is shown in Figure 1. Heating constitutes the primary energy expenditure in an average household. The second-largest energy consumers are household appliances, water heating, and lighting. In addition, air conditioning is provided during the summer. However, in this study, we assume that heating is provided by means other than electricity, such as natural gas. Consequently, the electrical load considered for the selected cities comprises household appliances, lighting, water heating, cooking, and air conditioning, all of which are categorised as electricity consumption.

Table 1. *Weather data of selected cities* [13]

#	Selected Cities	GHI (kWh/m^2/day)	Temperature (°C)	Wind Speed (m/s)
1	Artvin, Türkiye	3.83 (SMA)	12.4	1.3
2	Bingol, Türkiye	4.59 (SMA)	7.7	1.4
3	Karaman, Türkiye	5.01 (SMA)	12.0	2.3
4	Sanliurfa, Türkiye	5.15 (SMA)	18.7	2.6
5	Tekirdag, Türkiye	4.35 (SMA)	14.3	2.9
6	Trabzon, Türkiye	3.17 (SMA)	17.3	2.1
7	Yozgat, Türkiye	4.55 (SMA)	11.1	2.6



a b

Figure 1. ***a)*** *The breakdown of annual energy usage of an average household.* ***b)*** *Distribution of Türkiye's electricity consumption in households* [18].

Table 2 presents the average electricity consumption of households in the selected cities, along with their respective maximum and minimum values. In this study, we considered the average electrical energy consumption of households in these cities. As shown, the total electricity consumption ranges from 1844 kWh to 3152 kWh, depending on the level of development in each city. The table also provides the monthly average, maximum, and minimum consumption values for a typical household. These values are crucial for sizing on-grid and off-grid PV systems. Moreover, the peak power values listed in Table 2 are vital for ensuring the sustainability of off-grid PV systems.

The peak load value given in Table 2 shows the maximum load value in kW for each month. When making this calculation, the SAM uses the monthly energy consumption values entered for each city. To calculate the critical load, we considered the electrical appliances and lighting essential for an average dwelling, including items such as refrigerators, TVs, area lighting, and cooking appliances. For our calculations, we assumed that electrical appliances are energy-efficient (rated A and above) and that each household is equipped with the same type of appliances.

Incentives

In Türkiye, various grant supports and loan options are available to encourage electricity generation from solar energy. Solar energy incentives are provided by organizations such as Small and Medium Enterprises Development Organization (KOSGEB), Agriculture and Rural Development Support Institution (TKDK), Rural Development Investments Support Program (KKYDP), Technology Development Foundation of Türkiye (TTGV), and Türkiye Sustainable Energy Financing Facility (TurSEFF). Notably, the incentives offered by TKDK and KKYDP are covered by the Instrument for Pre-Accession Assistance Rural Development (IPARD) Program Fund, co-financed by the European Union and the Republic of Türkiye [20–24].

Table 2. *Total electricity consumption with monthly average minimum and maximum values* [19].

Cities	Electricity (kWh/year)	Mean (kWh/month)	Min (kWh/month)	Max (kWh/month)	Peak Power (kW)
Artvin	3152	262.7	168.1	472.8	1.42
Bingol	1844	153.7	98.3	276.6	0.83
Karaman	2296	191.3	122.5	344.4	1.04
Sanliurfa	2124	177.0	113.3	318.6	0.96
Tekirdag	2692	224.3	143.6	403.8	1.22
Trabzon	3252	271.0	173.4	487.8	1.47
Yozgat	2084	173.7	111.1	312.6	0.94

To support the construction of solar power generation facilities, VAT and custom exemptions are applied to the procurement of goods and services. In addition, corporate tax deductions ranging from 30% to 55% are offered based on the support region for rooftop PV applications. Furthermore, SGK employer premium incentives are provided for periods ranging from 6 to 12 years.

These incentive programmes categorise the provinces of Türkiye into 6 regions, and each region receives distinct treatment. For this study, we implemented solar energy incentive programmes applicable to PV systems in the provinces selected from different regions of Türkiye. Detailed information on these incentive programmes is provided in Table 3.

Table 3. *Regional incentive programs in selected cities* [24,25].

Regional Incentive Applications	Artvin	Bingol	Karaman	Sanliurfa	Tekirdag	Trabzon	Yozgat
Regions	4	6	3	6	1	3	5
VAT exemption	18%	18%	18%	18%	18%	18%	18%
Customs exemption	18-20%	18-20%	18-20%	18-20%	18-20%	18-20%	18-20%
Tax exemption (Corporate tax or Income tax)	70%	90%	60%	90%	50%	60%	80%
SSI employer premium exemption	6 y	10 y	5 y	10 y	2 y	5 y	7 y
SSI employer premium exemption rate	25%	-	-	-	-	-	35%
Investment contribution rate	30%	50%	25%	50%	15%	25%	40%
Investment place allocation	✓	✓	✓	✓	✓	✓	✓
Income tax withholding support	-	10 y	-	10 y	-	-	-
Property tax exemption	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
Stamp duty exemption	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%

Designing and Sizing the PV System

The PV systems designed for this study comprise several key components, including solar panels, inverters, battery packs, converters, and other electrical elements such as cables. Each component plays a specific role in ensuring efficient power generation and consumption within the PV system. Solar panels directly convert sunlight into DC. The inverter, a critical electronic device, converts DC into the commonly used AC in homes. Batteries are employed to store excess energy during periods of high sunlight for backup usage when needed. In addition, converters are used to regulate the variable voltage produced by PV panels, ensuring a more consistent current flow to the battery pack and inverter.

The selected solar panels have a designed operational lifespan of 25 years, whereas the inverter and batteries are expected to operate for 10 years each. The energy system design aims for a total lifespan of 25 years, with two replacements of both inverters and batteries anticipated during this period. To size the entire PV system, the practice recommended by the IEEE, based on the electricity demand of different households in the selected cities (refer to Table 4), is followed. According to IEEE standards [26], PV system sizing considers system losses, electrical load, sunlight availability, array load (A:L) ratio, shading, wiring, contamination, transformer losses, and household load.

Sizing was conducted for three different PV systems in the selected cities: on-grid, off-grid, and utility-scale PV systems. The schematic diagrams of these systems are shown in Figure 2, and the on-grid and off-grid system capacities corresponding to the electricity consumption of the cities are provided in Table 4. On-grid systems are connected to the local electricity grid and cater to the solar energy consumption of an average family in the cities. Off-grid systems, on the other hand, are not connected to the grid and use on-site energy storage. Additional battery sizing is performed for off-grid systems to ensure sufficient power supply throughout the year, particularly during months with minimal sunshine. The commercial utility-scale PV system is standardized at 3 MW for all cities.

Table 4. *Required PV capacity and corresponding design parameters*

#	Cities	Residential Standalone PV	Residential PV-Battery		Commercial Utility Scale
			PV Capacity	Battery Capacity	
1	Artvin, Türkiye	5 kW	5 kW	118 kWh	3 MW
2	Bingol, Türkiye	2.3 kW	2.3 kW	58 kWh	3 MW
3	Karaman, Türkiye	2.7 kW	2.7 kW	57 kWh	3 MW
4	Sanliurfa, Türkiye	2.3 kW	2.3 kW	53 kWh	3 MW
5	Tekirdag, Türkiye	3.6 kW	3.6 kW	84 kWh	3 MW
6	Trabzon, Türkiye	5.9 kW	5.9 kW	122 kWh	3 MW
7	Yozgat, Türkiye	2.7 kW	2.7 kW	65 kWh	3 MW

Throughout the simulation, the same module is used for every household to maintain location dependency. The residential rooftops are equipped with installed PV arrays, each consisting of half-cut 72 passivated emitter and rear contact (PERC) Si solar cells, with a maximum voltage (V_{MP}) of 41.56 V, maximum current (I_{MP}) of 10.95 A, efficiency of 20.97%, and maximum power (P_{MAX}) of 455 W_{dc}. For the inverter, the DC to AC ratio is set between 1.1 and 1.2, depending on the required installed capacity, to optimise panel use during non-peak hours. The size of the inverter varies with the selected cities to achieve the desired DC-to-AC ratio. To minimise inverting/transforming losses, the voltage for all systems, regardless of location, is set to 48 V [27–29].

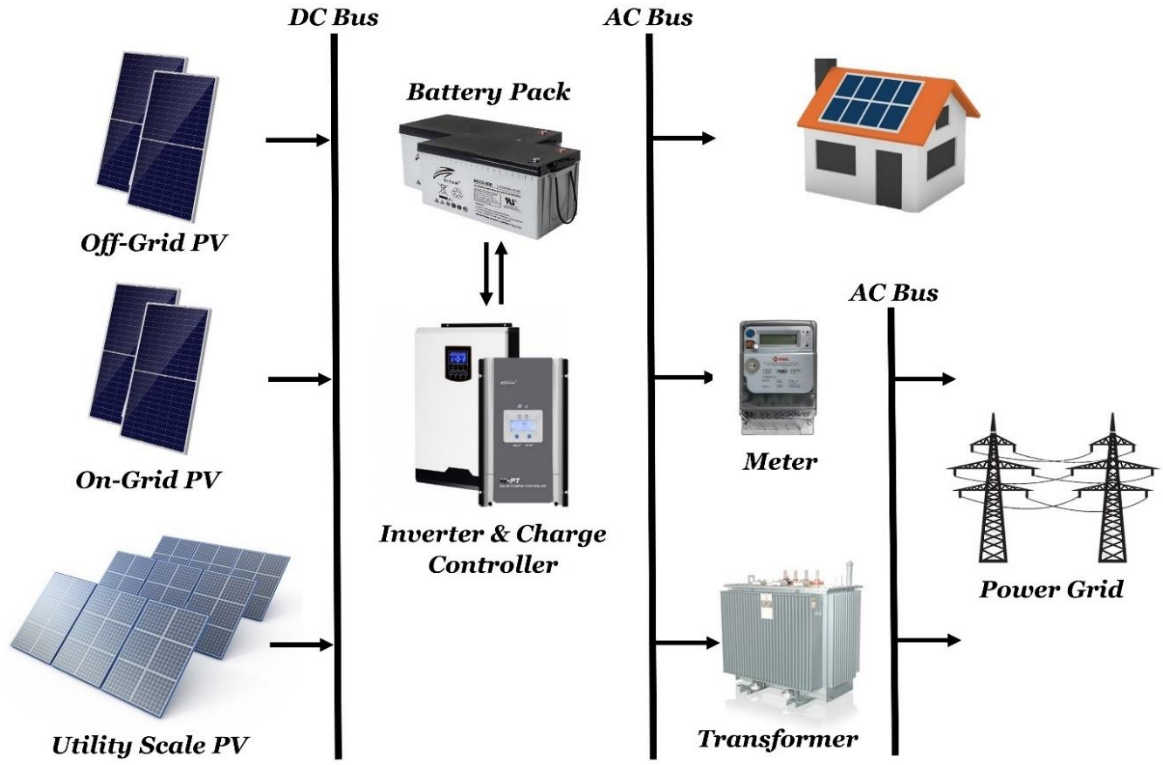


Figure 2. *Schematic diagram of pv systems*

Battery Sizing and Dispatch

In the design of off-grid PV systems, batteries play a crucial role in ensuring reliability and sustainability. The capacity of the battery required for each PV system depends on the duration for which it can support the household's critical load (Table 2), which varies among the selected cities. Autonomy in battery sizing is influenced by factors such as solar radiation variability, load predictability, and system availability. To calculate the appropriate battery size for the PV systems while adhering to IEEE standards, the IEEE Recommended Practice for Sizing Batteries for Standalone PV Systems [30] is applied.

Table 5. *Battery Specifications of the off-grid PV System*

Cities	Battery Size (A·h)	Days of Autonomy	Max Daily Load (A·h)
Artvin	2462.5	6	328.3
Bingol	1200.5	5	192.1
Karaman	1195.8	4	239.2
Sanliurfa	1106.3	4	221.3
Tekirdag	1752.6	5	280.4
Trabzon	2540.6	6	338.8
Yozgat	1356.8	5	217.1

Table 5 presents the battery specifications corresponding to the selected cities and their respective PV system sizes. The IEEE standards advocate a maximum depth of discharge (DOD) of 80% and a maximum daily DOD of 20%, with an end-of-life capacity of 80%. Following these guidelines, the batteries in the PV systems consistently operate between 20% and 80% capacity optimising the battery's lifespan and the overall number of battery cells used (in series) in the system.

Furthermore, the number of days of autonomy varies depending on the solar insolation of each location:

- Locations with solar insolation below 4.0 kWh/m^2/day are provided with 6 days of autonomy.
- Locations with solar insolation between 4.0 kWh/m^2/day and 4.7 kWh/m^2/day are allocated 5 days of autonomy.
- Lastly, locations with solar insolation exceeding 4.7 kWh/m^2/day are granted 4 days of autonomy.

As shown in Table 5, Trabzon requires the largest battery size because of its high daily load and lower insolation, while Sanliurfa and Karaman have the smallest battery sizes because of their high insolation levels and lower electric load demands.

Financial Parameters

In the financial analysis, we assess the economic viability of PV system projects in Türkiye. The costs of on-grid and off-grid PV systems are determined using reports published by the National Renewable Energy Laboratory (NREL) [31], [32], whereas for utility-scale PV systems, the Renewable Power Generation Costs in 2021 report [33] published by the International Renewable Energy Agency is used. The annual loan interest was 22%, and the real discount rate was 9.75%. Other important financial parameters, such as the inflation rate, were determined by taking the average of the last 20 years (January 2023 values) [34], [35]. In addition, for commercial utility-scale PV systems, the solar power purchase agreement (PPA) rate is implemented at 0.133$/kWh [36–38]. This data provides a detailed analysis of past performance, allowing future projects to be evaluated on a reliable basis. In addition, these data help predict future trends in the energy sector, enabling the development of sustainable and effective energy solutions.

To assess the economic viability of the study in the selected cities, we evaluated key metrics such as the levelized cost of electricity (LCOE), the levelized cost of storage (LCOS), the net present value (NPV), and the payback period of the investment [39], [40]. The LCOE represents the total cost incurred over the lifecycle of the PV system divided by the total energy produced during the same period, typically expressed in cents per kWh. This calculation considers equity investments, operating expenses, debt costs, and taxes, while also considering incentives, salvage value, and tax benefits. The LCOE is determined using the SAM software;

$$LCOE \frac{-C_0 - \frac{\sum_{n=1}^{N} C_n}{(1+r_{nominal})^n}}{\frac{\sum_{n=1}^{N} Q_n}{(1+r_{real})^n}} \qquad \textbf{Eq. 1}$$

where C_n is the annual project costs in year n, C_0 is the project's equity investment amount, Q_n (kWh) electricity produced by the system in year n, N is the analysis period, real is the real discount rate and $r_{nominal}$ is the nominal discount rate.

To comprehensively analyse the impact of storage in off-grid systems, we consider the storage cost or LCOS. LCOS considers various factors, including the initial cost of the battery (installation, maintenance, and replacement), the cost of electricity needed to charge the battery, and the degradation of battery capacity over time. These considerations are crucial in assessing the overall design of off-grid PV systems. The LCOS calculations are based on the methods described in [41] and are calculated accordingly;

$$LCOS = \frac{investment\ cost + \sum_{n}^{N} \frac{O\&M\ cost}{(1+r)^n} + \sum_{n}^{N} \frac{Charging\ cost}{(1+r)^n} + \sum_{n}^{N} \frac{EOL\ cost}{(1+r)^{N+1}}}{\sum_{n}^{N} \frac{Discharge\ cost}{(1+r)^n}} \quad \textbf{Eq. 2}$$

where O&M is the operation and maintenance, r is the discount rate and EOL is the end-of-life cost.

The NPV is also another metric that is commonly used, which measures the cost-effectiveness of a PV system by taking both cost and revenue into account.

$$NPV = \sum_{n=0}^{N} \frac{C_n}{(1+r)^n} \quad \textbf{Eq. 3}$$

where N is the analysis period, C_n represents the return after tax and r is the discount rate [42].

RESULTS AND DISCUSSION

The evaluation of PV systems in the selected cities was conducted through simulation using SAM. The results obtained from the simulation cover both technical and economic aspects, providing valuable insights into the feasibility of PV systems in these locations.

Technical Results: The simulation yields detailed technical data, including electricity generation, losses, and efficiency. By analysing electricity generation patterns, we can understand the system's capability to harness solar energy and produce electricity. Assessing losses allows us to identify potential areas of improvement in the PV system's design and operation. Efficiency measurements provide valuable information on the system's overall performance and effectiveness in converting sunlight into electrical energy.

Economic Viability: The economic viability of PV systems is evaluated using essential financial metrics. The payback period indicates the time required for the PV system's initial cost to be recouped through electricity generation and savings. The LCOE quantifies the average cost of producing electricity over the system's lifetime, incorporating various factors such as investment costs, operating expenses, and incentives. In addition, the LCOS is analysed for off-grid systems to understand the economic impact of battery storage, considering battery-related costs and performance over time.

The results and analysis from the simulation will be discussed in detail to provide valuable insights into the technical and economic feasibility of implementing PV systems in the selected cities. This discussion will shed light on the potential challenges, benefits, and opportunities associated with each type of PV system (on-grid, off-grid, and utility-scale) and will enable us to draw meaningful conclusions to support the development of sustainable and efficient solar energy solutions.

Technical Analysis

The solar radiation received by cities has a significant impact on electricity production, and maximizing production is achieved through panel tilt angle optimisation and monitoring systems. Different tilt angles are applied to ensure optimal sun exposure on the PV modules. The intensity of solar radiation received on the surface of a PV module at a given angle of inclination is measured by array plane (POA) radiation. Figure 3 illustrates the POA after accounting for shading and fouling losses, which determine the capacity factor (CF) of a PV system. The POA values vary between 373 kWh/month in Bingol and 1288 kWh/month in Artvin during the winter season.

Notably, it is crucial to recognise that POA values are highly dependent on the total surface area of the PV modules. This explains why regions with less sunlight exposure, such as Trabzon and Artvin, receive higher irradiation values than regions such as Sanliurfa and Karaman. Moreover, the CF is defined as the ratio of the actual electrical energy output over a given period to the theoretical maximum electrical output during that period and is listed in Table 6 for the selected cities. Sanliurfa and Karaman have the highest CF for a PV system because of their higher insolation values of 5.15 kWh/m^2/day and 4.89 kWh/m^2/day, respectively. Conversely, the cities with the lowest CF values are Trabzon and Artvin, as they are located in northern Türkiye and experience fewer sunny days.

Comparing the CF values of the selected cities with the latest IRENA report [33], which indicates an average CF of 17.2% for utility-scale PV systems in 2021, it is evident that all cities, except Trabzon and Artvin, surpass the utility-scale average in Table 6 for residential-scale systems.

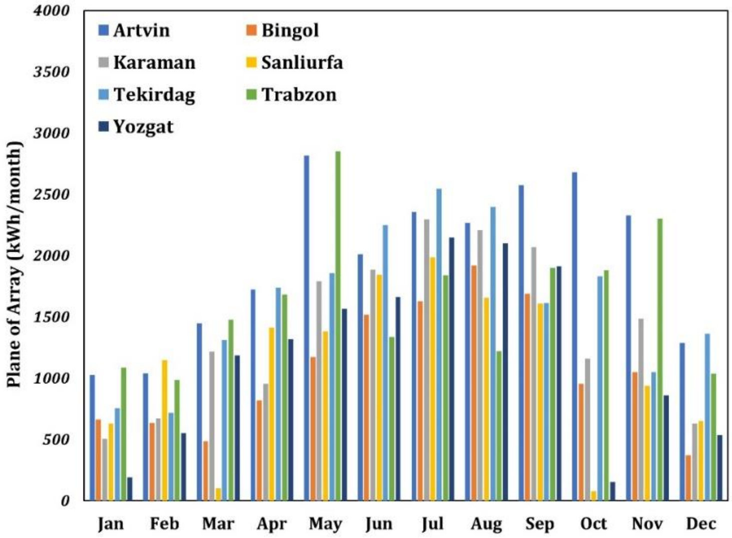


Figure 3. *Plane of array (POA) incidents for the PV systems installed in selected cities.*

Table 6. *Technical results of PV systems for selected cities*

#	Cities	Off-Grid & On-Grid		Utility Scale	
		Capacity Factor	**Annual production (kWh)**	**Capacity Factor**	**Annual production (kWh)**
1	Artvin	16.0%	6974	16.0%	4,204,588
2	Bingol	18.7%	3735	18.6%	4,911,718
3	Karaman	19.9%	4754	19.7%	5,186,336
4	Sanliurfa	20.6%	4099	20.4%	5,380,968
5	Tekirdag	18.3%	5825	18.1%	4,767,513
6	Trabzon	13.0%	6204	12.9%	3,410,951
7	Yozgat	18.4%	4401	18.3%	4,808,822

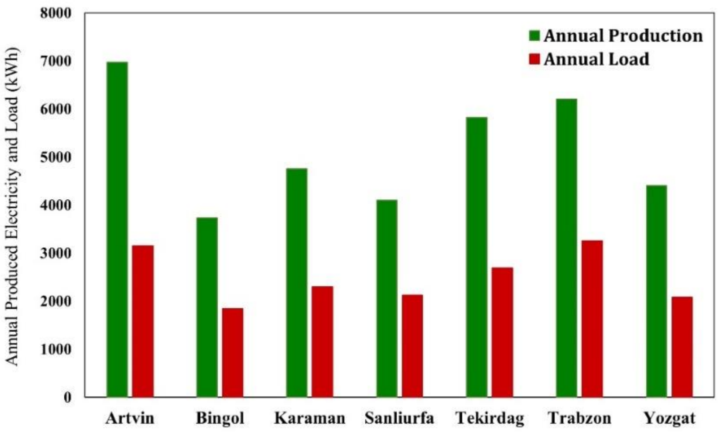


Figure 4. *Annual produced energy from the PV systems and corresponding load.*

In on-grid and off-grid PV systems designed to meet the actual electrical load capacity for each household in the cities (see Figure 4), the results demonstrate varying energy production levels due to different insolation rates. Figure 5 illustrates the monthly required electrical load for the selected cities along with the corresponding electrical energy generated from the PV systems. Trabzon exhibited the highest energy surplus, approximately 516 kWh/month in May, followed by Artvin with 453 kWh/month and Tekirdag with 402 kWh/month in April. Cities with lower sunlight exposure require a higher number of PV modules to meet the demand, resulting in a surplus of energy during the summer months.

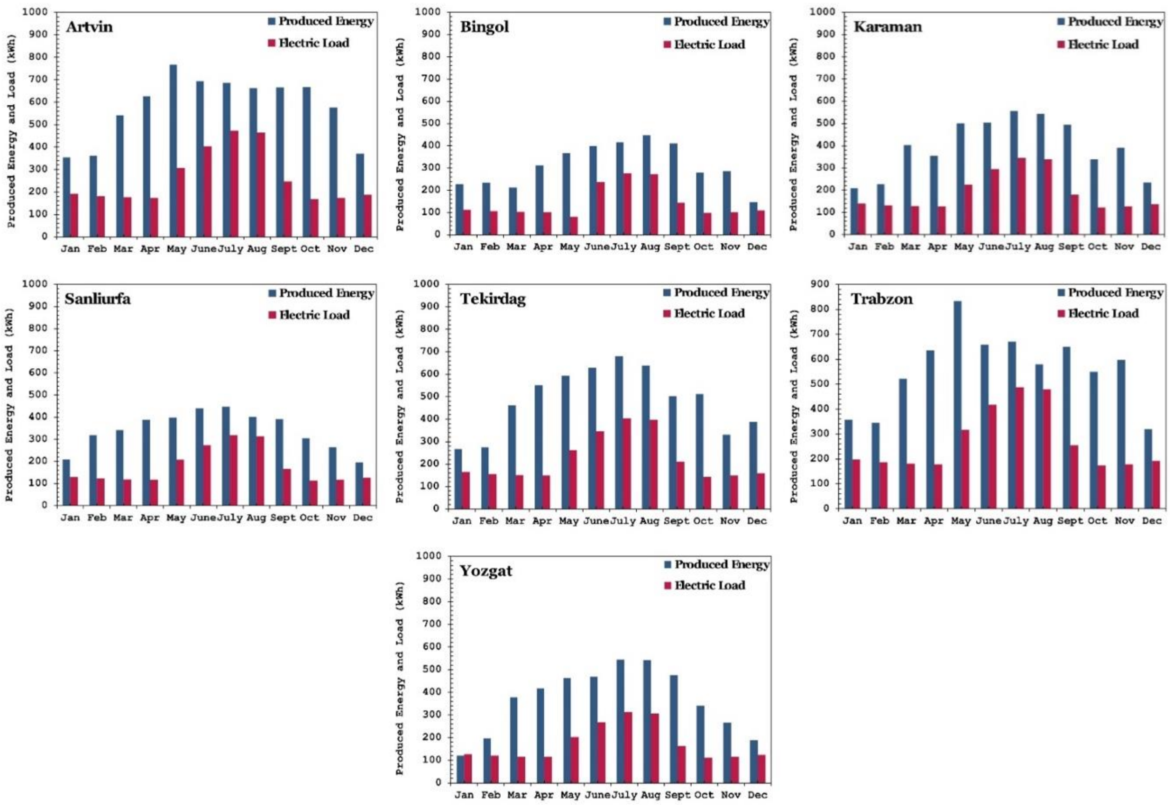


Figure 5. *Monthly average produced energy and electric load in selected cities.*

For off-grid PV systems in cities, Figure 6 presents a detailed energy flow analysis between the battery and load. During low-load months such as January, February, and March, the energy flow from the battery and PV system to the load is inversely proportional due to limited radiation.

Conversely, during high-load months, the flow from the PV system itself to the load is higher. The southern provinces of Türkiye, such as Sanliurfa and Karaman, demonstrate a more evenly distributed load, and the number of PV modules effectively provides the required electricity. Hence, these cities do not generate as much surplus energy during the summer months as other cities.

Figure 6 also highlights the role of batteries in off-grid PV systems, where the battery is discharged on a daily cycle. The battery can only be charged from the system, and the minimum depth of discharge is 30%. Although PV systems are sized for worst-case scenarios, batteries are essential at night and on low-light days when PV generation is insufficient for the load. The PV system prioritises meeting the required load first and then charges the battery. During periods of excess PV production, the battery is recharged and remains at full power until needed. The battery comes into play when the electrical load requires more power than the PV system can provide. As seen in the analysis, batteries play a pivotal role in maintaining the sustainability of off-grid PV systems. During sunlit months with sufficient sunlight, such as in Sanliurfa, Karaman, Bingol, and Tekirdag, the battery remains fully charged. However, cities such as Artvin and Trabzon, which have lower light intensity due to their locations, require larger batteries and rely on battery usage during the summer months.

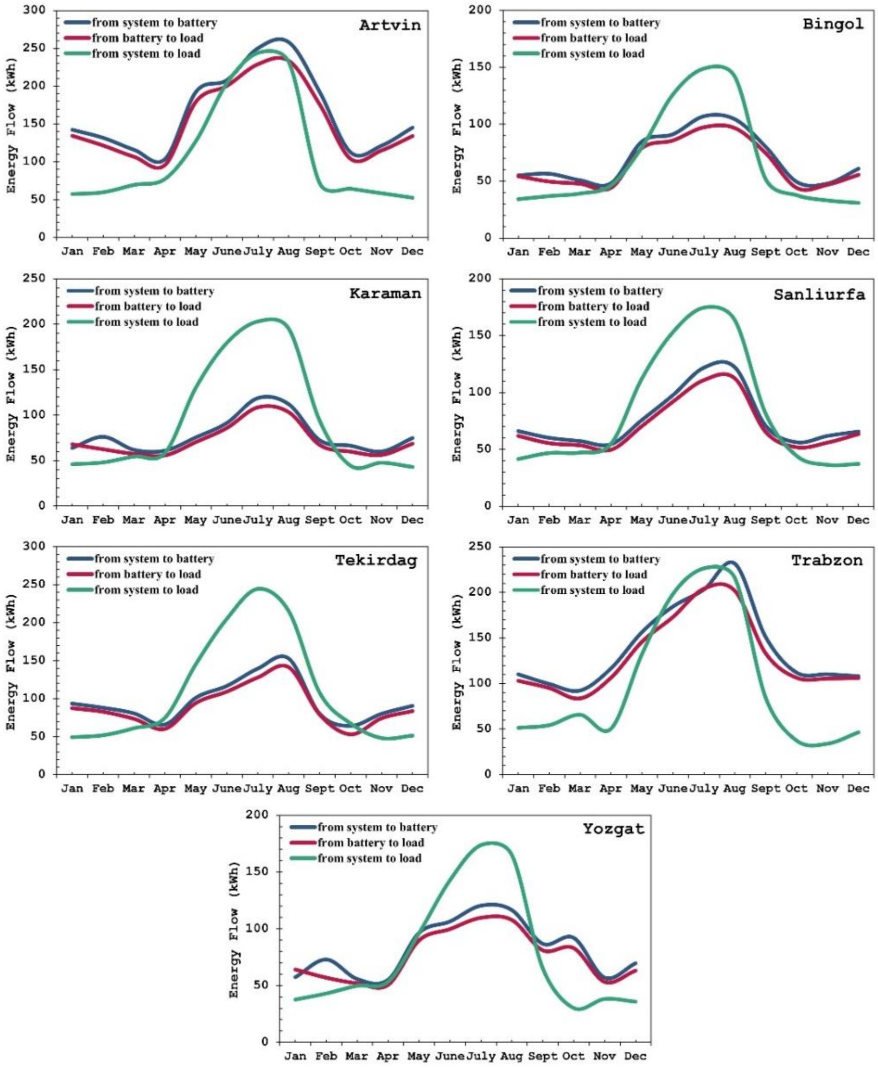


Figure 6. *Energy flow in off-grid PV systems*

Economic Analysis

The economic analysis of PV systems plays a crucial role in determining their feasibility and implementation. Several parameters are considered in the cost analysis, including direct capital costs such as module, inverter, controller, battery, and labour costs, as well as indirect costs such as permitting, engineering operations, and overheads. These costs were applied uniformly across all selected cities (see Table 7). However, in off-grid PV systems, the varying battery capacity requirements in different cities lead to differences in system costs. The operating and maintenance cost during the system's lifetime is $10/kW for both on-grid and off-grid systems in residential projects, whereas it is $18/kW for commercial utility-scale systems [33]. The simulations assume that the entire installation cost is financed through a 25-year mortgage without any upfront payment. The loan rates used in the simulation represent the average commercial loan rates offered by banks in the country over 25 years. Additionally, income tax for utility-scale PV systems is set at 12%, while on-grid and off-grid PV systems on rooftops have a zero-sales tax rate due to the absence of taxable income. The calculations also consider the incentives mentioned in Table 3, considering the regional incentive programs of the cities.

Table 7. *Installation costs of PV systems in selected cities* [43]

#	Cities	Total Installed Cost ($/$W_{dc}$)		
		On-grid PV	Off-grid PV	Utility Scale
1	Artvin	2.52	4.88	1.10
2	Bingol	2.52	5.07	1.10
3	Karaman	2.52	4.61	1.10
4	Sanliurfa	2.52	4.85	1.10
5	Tekirdag	2.52	4.83	1.10
6	Trabzon	2.52	4.75	1.10
7	Yozgat	2.52	4.90	1.10

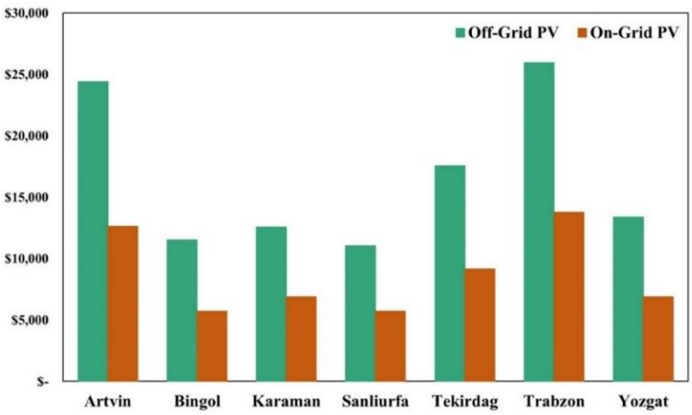


Figure 7. *Comparison of installation cost of on-grid and off-grid PV systems in cities.*

Table 7 presents the financial input values for the selected cities, with direct capital costs encompassing all components such as modules, inverters, balance of system equipment (BOS), battery, and labour, while indirect costs include permitting, overheads, and environmental studies. The total installed cost ($/$W_{dc}$) represents the cost per nameplate DC capacity of the PV systems. However, the total installed cost ($/$W_{dc}$) is not directly proportional to the total cost because of variations in electricity consumption and sunshine duration among the cities.

For on-grid PV systems, the investment cost is $2.52/$W_{dc}$ across all cities, whereas for utility-scale commercial PV systems, the investment cost is $1.10/$W_{dc}$. In the case of off-grid PV systems, the varying battery sizes required by cities lead to investment costs ranging from $4.61 to $5.07/$W_{dc}$. Bingol and Yozgat have the highest cost per $/$W_{dc}$, amounting to $5.07/$W_{dc}$ and

$4.90/W$_{dc}$, respectively. Conversely, Karaman has the lowest \$/W$_{dc}$ cost in off-grid PV systems, with an investment cost of \$4.61/W$_{dc}$.

Figure 7 provides a comparison of investment costs between rooftop on-grid and off-grid PV systems for the selected cities. Provinces with high electricity consumption require larger PV and battery capacities, resulting in higher investment costs. Trabzon and Artvin have the highest PV investment costs, with system costs of $13,761 and $12,614 for on-grid PV systems and $25,963 and $24,416 for off-grid PV systems, respectively. On the other hand, Sanliurfa and Bingol have the lowest PV investment costs, with costs of $5,734 in on-grid PV systems and $11,532 in off-grid PV systems.

Table 8 presents the actual LCOE, LCOS, and NPV values, which are financial output parameters obtained from the simulations. LCOE and LCOS are critical metrics for evaluating PV systems because they encompass all costs, including capital costs (direct and indirect), operating expenses, and term debt costs. The actual LCOE is particularly suited for long-term analysis, considering inflation over the project's lifespan, making it a valuable indicator for this study. Additionally, the current electricity price in Türkiye is considered to be 0.09 $/kWh [44] (assuming a single tariff throughout the day) for comparing the energy production costs of PV systems. When comparing actual LCOE values with the current electricity prices (see Table 8), all cities except Trabzon demonstrate grid parity, implying that electricity produced by PV systems is cheaper than the current electricity prices. The inclusion of battery costs in the total cost of off-grid PV systems and subsequent LCOE calculations warrants the inclusion of LCOS in Table 8 to understand the impact of the battery system.

While the LCOE is a beneficial metric for financial feasibility assessment, it is best considered in conjunction with other indicators. The most crucial of these is NPV, as shown in Table 8 for all PV systems. NPV is significantly influenced by factors such as inflation rate, annual loan rate, and discount rate. In off-grid and utility-scale PV systems, the NPV value is negative for all cities. On the other hand, positive NPV values were observed in all cities except Trabzon for on-grid PV systems. Notably, Karaman and Sanliurfa exhibited the highest positive NPV values in on-grid PV systems. In general, all selected cities can transition to PV systems if they are considered in terms of reasonable NPV and viewed not merely as an investment, but rather as cities seeking energy independence and self-generation capabilities.

Table 8. *Financial output parameters to evaluate the feasibility of PV systems.*

Cities	Off-Grid PV			On-Grid PV		Utility Scale PV	
	LCOE real ($/kWh)	LCOS real ($/kWh)	Net Present Value ($)	LCOE real ($/kWh)	Net Present Value ($)	LCOE real ($/kWh)	Net Present Value ($)
Artvin	0.159	0.702	-7,893	0.092	451	0.049	-454,401
Bingol	0.140	0.788	-4,056	0.079	713	0.042	-283,301
Karaman	0.120	0.702	-4,242	0.075	1,081	0.040	-216,880
Sanliurfa	0.122	0.668	-3,632	0.072	1,031	0.039	-170,459
Tekirdag	0.137	0.828	-6,278	0.081	972	0.043	-318,424
Trabzon	0.191	0.850	-9,786	0.115	-747	0.060	-645,792
Yozgat	0.138	0.757	-4,747	0.081	769	0.043	-307,801

Sensitivity Analysis of the LCOE and the NPV

The LCOE and NPV values obtained from the SAM simulations for the selected cities can be further examined through a sensitivity analysis. In this analysis, input parameters such as the discount rate (DR), the loan rate (LR), the conversion efficiency of the PV modules (η), and solar irradiation (SI) are varied to understand their impact on the selected output parameters. By analysing the sensitivity of DR, LR, and SI to LCOE and NPV, we gain insights into how changes in these parameters affect the performance of the PV systems. Probability distributions are applied to DR, LR, and SI, and their variations are evaluated for all PV systems in the selected cities. The black line in the middle of the figures represents the simulated real LCOE values of the PV systems with the actual inputs for the selected city, while the coloured bars depict the sensitivity of the PV systems to these input parameters.

On-Grid PV

The discount rate (DR) and loan rate (LR) are financial input parameters that are altered within the probability distribution range from zero to the maximum point. The LCOE is directly proportional to DR and LR, meaning that higher DR and LR values result in higher LCOE values. On the other hand, the conversion efficiency of the PV modules (η) and solar irradiation (SI) are in an indirect correlation with the LCOE. As these parameters increase, the LCOE decreases.

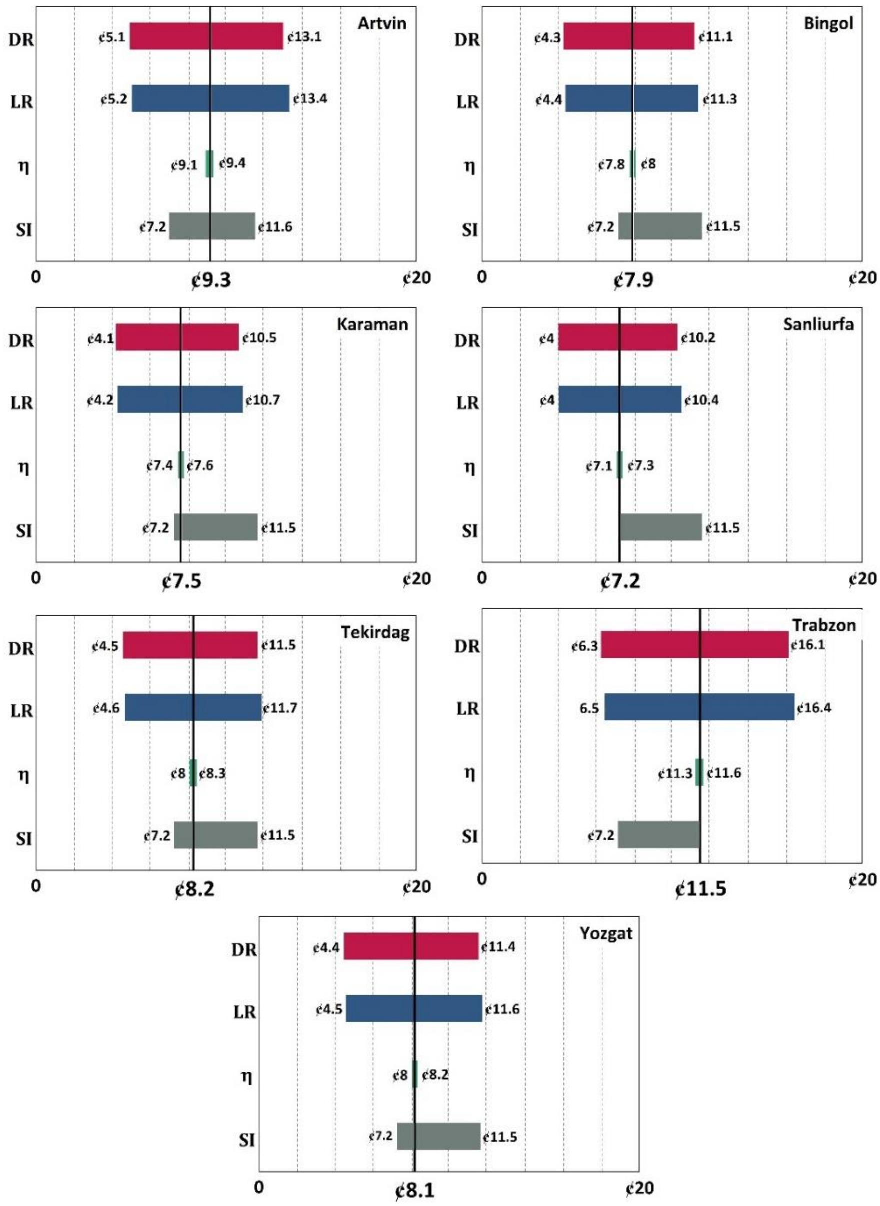


Figure 8. *Sensitivity analysis of discount rate (DR), loan rate (LR), module efficiency (η) and solar radiation (SI) on LCOE values of on-grid PV systems*

In addition to analysing the sensitivity of LCOE, a similar analysis is performed for NPV. By understanding the sensitivity of these key parameters, policymakers and stakeholders can make informed decisions and optimise the design and implementation of PV systems to achieve greater economic viability and energy independence in the selected cities.

Figure 8 illustrates the sensitivity analysis of the LCOE for on-grid PV systems. The loan rate and solar radiation are the parameters that have the most significant impact on the LCOE, followed by the discount rate. Cities with higher solar radiation levels, such as Sanliurfa and Karaman, are less affected by changes in solar irradiation than cities with lower sunlight exposure, such as Trabzon and Artvin. On the other hand, all cities, except Trabzon, have an LCOE equal to or lower than the grid electricity price. This indicates that an on-grid PV system can generate electricity in almost every region of Türkiye at a cost that is competitive or lower than the grid electricity price.

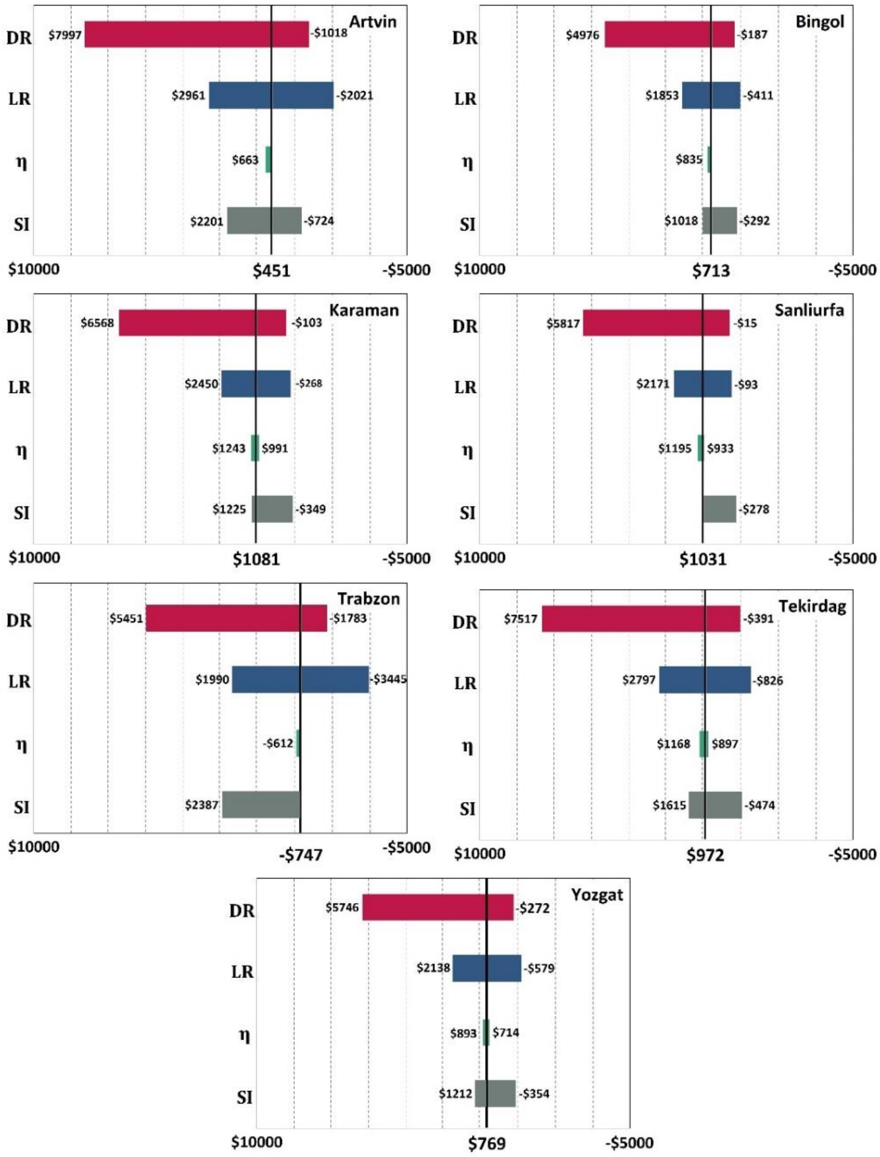


Figure 9. *Sensitivity analysis of discount rate (DR), loan rate (LR), module efficiency (η) and solar radiation (SI) on NPV values of on-grid PV systems*

Regarding the NPV of on-grid PV systems (Figure 9), financial constraints, represented by loan rates, have the most significant impact on the NPV. Additionally, the module efficiency as a performance input plays a substantial role in determining the feasibility of the PV project. The positive NPV values in almost all cities indicate that at the end of the project, these on-grid PV systems can result in profitable returns. These results highlight the importance of suitable mortgage rates for PV projects offered by stakeholders such as governments and banks, as they can significantly influence the feasibility and adoption of PV in the selected cities.

By considering the sensitivity of these parameters, policymakers and investors can identify strategies to optimize the financial viability and performance of on-grid PV systems, enabling wider adoption of renewable energy sources in Türkiye.

Off-Grid PV

Similar to on-grid PV systems, off-grid PV systems are also affected by various parameters. Figure 10 demonstrates that the discount rate has the most significant impact on the LCOE, followed by the loan rate and insolation.

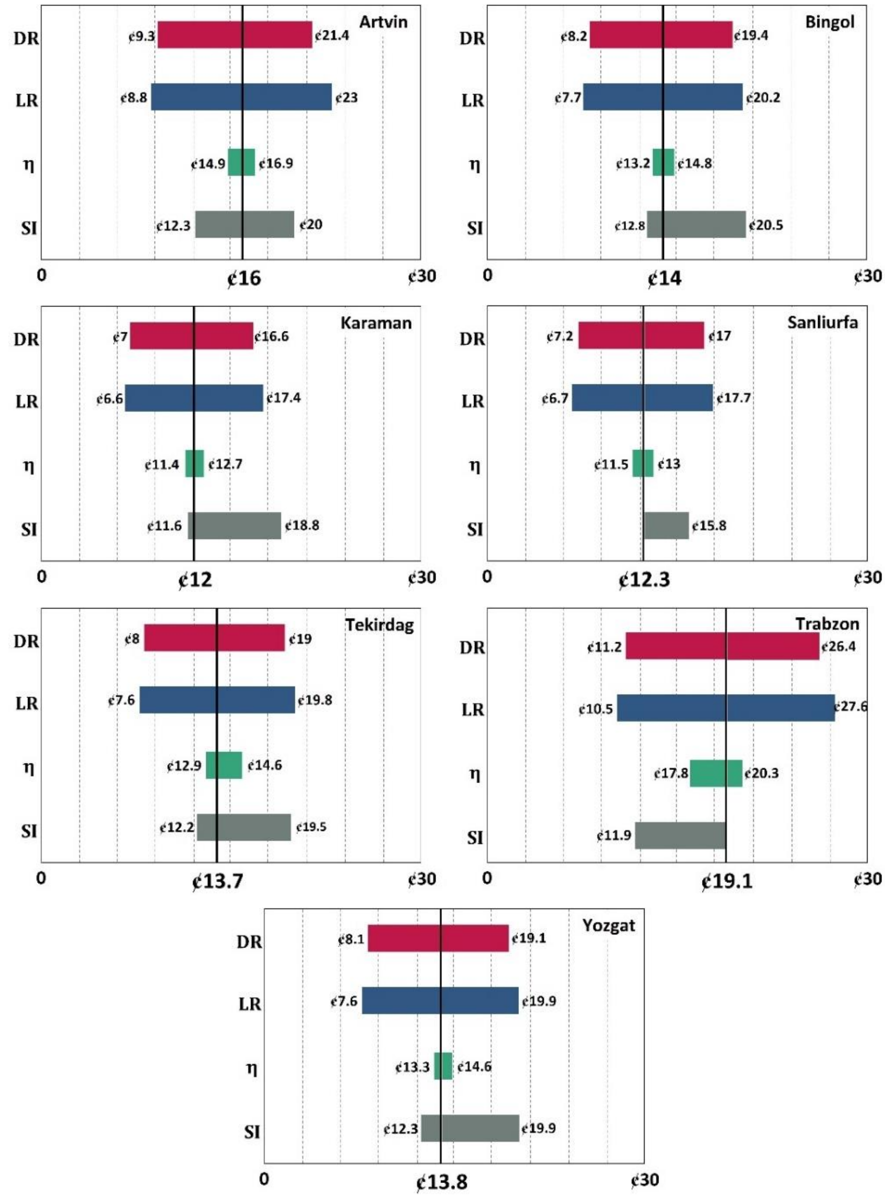


Figure 10. *Sensitivity analysis of discount rate (DR), loan rate (LR), module efficiency (η) and solar radiation (SI) on LCOE values of off-grid PV systems*

Cities with higher solar exposure, such as Karaman and Sanliurfa, prioritise the discount and loan rates, whereas other cities have a different pattern. Any improvement in the loan interest rate and discount rate leads to substantial reductions in the LCOE of the system. To promote the adoption and applicability of off-grid PV systems, implementing support programmes and incentive policies is crucial.

Considering the NPV values for off-grid PV systems (Figure 11), a different aspect emerges. The higher system cost of off-grid systems compared to on-grid systems makes the NPV value more significant in terms of investor preference. The duration of sunshine has little effect on NPV across all cities. Conversely, the loan interest rate plays a substantial role in determining the NPV. Additionally, advancements in battery technology and cost reductions can facilitate the integration of PV-battery systems, further increasing the attractiveness of off-grid PV systems.

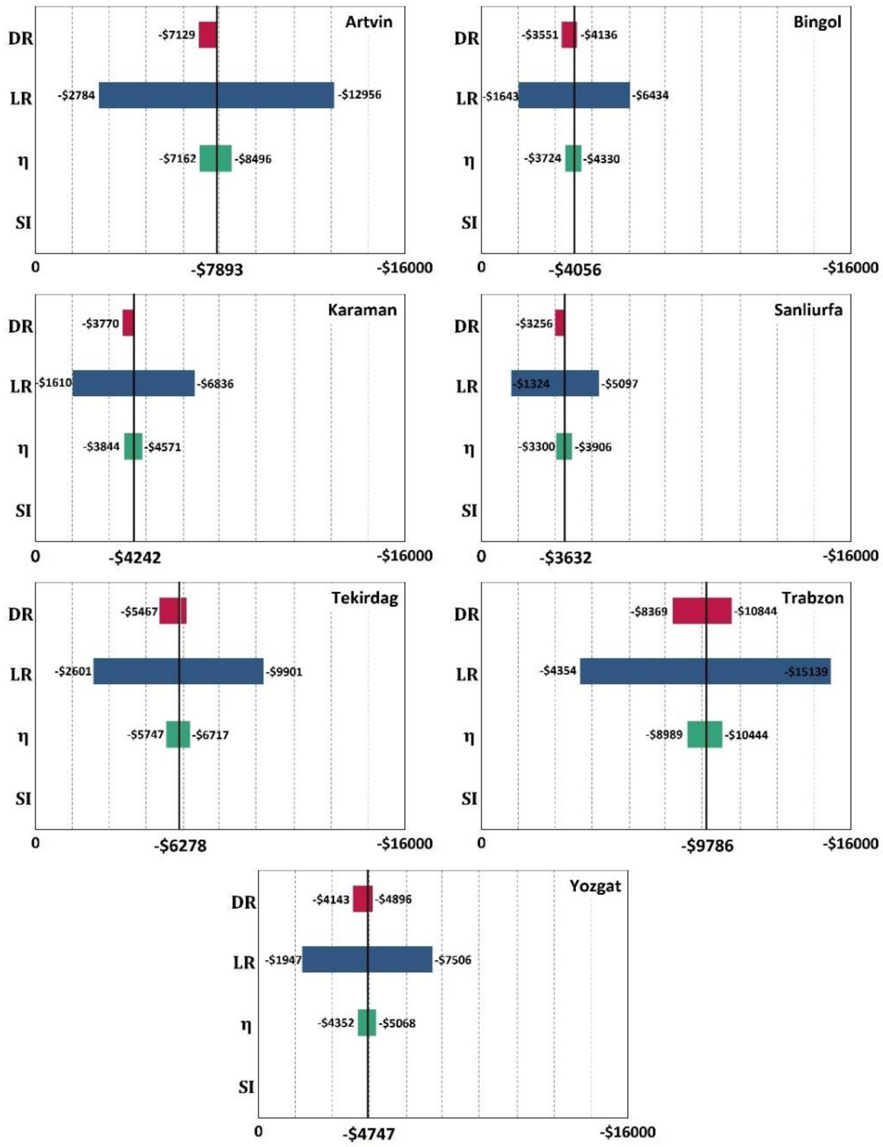


Figure 11. *Sensitivity analysis of discount rate (DR), loan rate (LR), module efficiency (η) and solar radiation (SI) on NPV values of off-grid PV systems*

To encourage the widespread implementation of off-grid PV systems, policymakers and investors should focus on providing favourable loan interest rates and creating a supportive environment for battery technology advancements. These measures would enhance the feasibility and appeal of off-grid PV systems, making them a promising alternative for electricity generation in the selected cities.

Utility Scale PV

Now, let us focus on the sensitivity analysis of LCOE and NPV values for large-scale commercial PV systems in the selected cities. Figure 12 illustrates the sensitivity analysis of LCOE values, while Figure 13 presents the sensitivity analysis of NPV values.

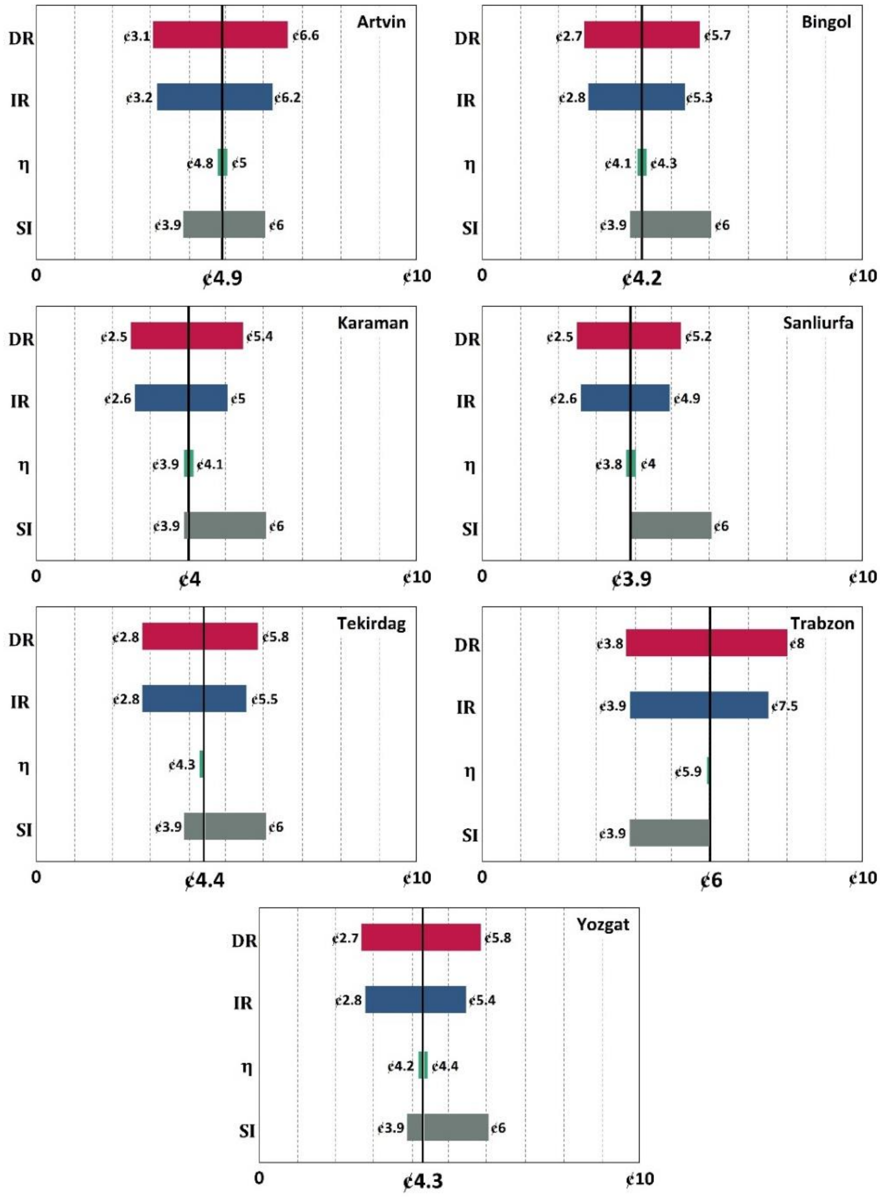


Figure 12. *Sensitivity analysis of discount rate (DR), interest rate (IR), module efficiency (η) and solar radiation (SI) on LCOE values of utility-scale PV systems.*

In utility-scale PV systems, the LCOE value of 4¢/kWh across all regions of Türkiye establishes a competitive foundation for electricity generation. As in other PV systems, this value can be further reduced by improving the discount and loan rates. Notably, cities such as Karaman, Sanliurfa, and Bingol are in a more advantageous position for electricity generation using PV systems than other cities (see Figure 12). Interestingly, the power η showed the lowest correlation with LCOE for all cities. This suggests that while the variation in η should not be overlooked, it would be more beneficial to focus on other uncertainties. This finding may also highlight the potential impact of new and emerging solar cell technologies on LCOE.

In terms of NPV values, all cities showed negative values (see Figure 13). As mentioned earlier in the sensitivity analysis of other PV systems, a positive NPV value can be achieved in all cities by primarily considering the interest and discount rates. In this context, steps taken by banks and governments to support PV systems will play a crucial role in accelerating the transition to large-scale commercial PV systems.

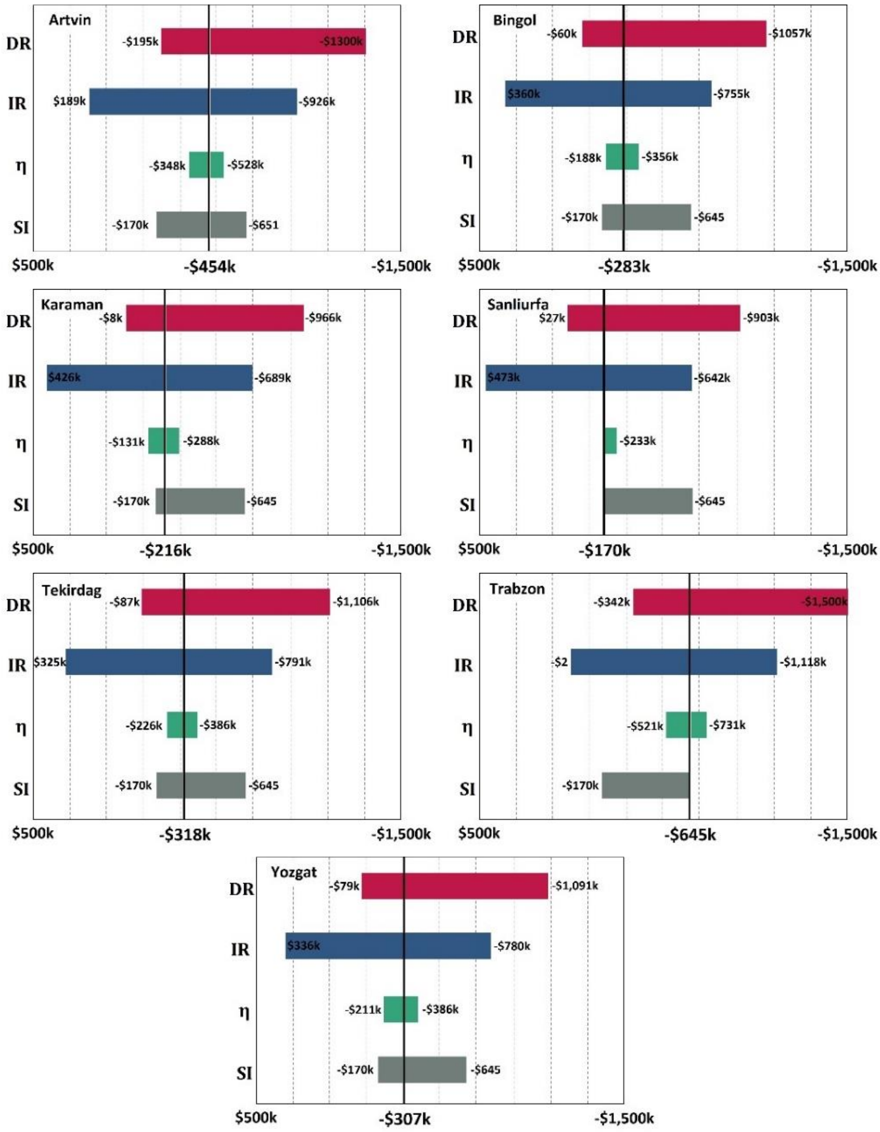


Figure 13. *Sensitivity analysis of discount rate (DR), interest rate (IR), module efficiency (η) and solar radiation (SI) on NPV values of utility-scale PV systems.*

Considering the competitive LCOE values of utility-scale PV systems and the potential for positive NPV with adequate financial support, large-scale commercial PV projects hold promise as an economically viable and sustainable option for electricity generation in Türkiye's selected cities. Policymakers and financial institutions should collaborate to provide favorable financial conditions and incentives to promote the widespread adoption of utility-scale PV systems, ultimately contributing to a more sustainable and greener energy landscape for the country.

CONCLUSION

This study assessed the technical and economic feasibility of photovoltaic (PV) systems in various cities across Türkiye using the System Advisor Model (SAM). The simulation results provide detailed insights into the electricity generation, losses, efficiency, and economic viability of on-grid, off-grid, and utility-scale PV systems.

The solar radiation received by the cities significantly influenced electricity production, with maximum generation achieved through panel tilt angle optimization and monitoring systems. The capacity factor (CF) of the PV systems varied based on the total surface area of the PV modules and the solar radiation in each location. Sanliurfa and Karaman had the highest CFs because of their higher insolation levels. On the other hand, Trabzon and Artvin, located in northern Türkiye with less sunlight, had lower CFs. Overall, the PV systems in all selected cities, except Trabzon, showed promising capacity factors, even surpassing the average CF of utility-scale PV systems reported in the latest IRENA report.

The financial parameters, including total installed costs, LCOE, LCOS, and NPV, were evaluated to assess the economic viability of PV systems. The LCOE and NPV analyses revealed that on-grid PV systems in all cities, except Trabzon, were at grid parity, indicating that the cost of electricity generated from PV systems was lower or equal to the current electricity prices in the region. Off-grid PV systems, which cost almost twice as much as on-grid systems, showed positive NPV values for all cities, highlighting their financial attractiveness to investors. In contrast, utility-scale PV systems, with an LCOE of 4¢/kWh across all cities, presented a competitive basis for electricity generation. However, the NPV values for utility-scale systems were negative, suggesting that further financial support and incentives are needed to promote the transition to large-scale commercial PV projects.

The sensitivity analysis of LCOE and NPV values provided valuable insights into the impacts of key input parameters such as discount rate, loan rate, PV module efficiency, and solar irradiation. In all PV systems, financial parameters, particularly the discount rate and loan rate, had the most significant influence on both LCOE and NPV. In contrast, solar irradiation had a more substantial impact on LCOE in on-grid and off-grid systems, whereas power efficiency (η) showed a weaker correlation with LCOE in utility-scale PV systems.

The study's results indicate that PV systems hold considerable potential for electricity generation in Türkiye's selected cities. However, certain policies and financial support mechanisms are crucial for maximizing the adoption of PV systems. Favorable interest rates, incentives, and government-backed loan programs would enhance the economic viability of PV projects and encourage their widespread implementation. In addition, advancements in battery technology and cost reductions can improve the feasibility of off-grid PV systems, making them more appealing to investors.

Conflict of Interest

The authors have no conflicts of interest to disclose for this study.

Authorship Contribution Statement

B.A.: Data Curation, Formal Analysis, Investigation, Writing – Original Draft, **S.A.:** Supervision, Writing – Review & Editing, **M.Y.:** Resources, Writing – Review & Editing, **M.S.B.:** Supervision, Software, Writing – Review & Editing **V.U.:** Supervision, Conceptualization, Investigation, Writing - Review & Editing

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