Black Sea Journal of Engineering and Science
doi: 10.34248/bsengineering.1813085

Open Access Journal
e-ISSN: 2619 – 8991

Research Article
Volume 9 - Issue 2: 469-479 / March 2026

PERFORMANCE ASSESSMENT OF BALCONY PLUG-AND-PLAY PHOTOVOLTAIC SYSTEMS IN ISTANBUL

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Abstract: In recent years, balcony plug-and-play photovoltaic (PV) systems have experienced significant growth in Europe, driven by rising electricity prices, environmental awareness, and ease of installation. These modular systems can be directly connected to a household socket without professional installation, making them ideal for apartment residents lacking rooftop access. Their investment cost per kilowatt is nearly half that of conventional rooftop PV, lowering the entry barrier for urban households seeking to reduce energy bills and carbon emissions. This study analyzes the performance of balcony plug-and-play PV systems for Istanbul, Türkiye. Using BEopt building energy simulation software, typical low-, medium-, and high-electricity consumption apartments were modeled to estimate annual electricity demand under Istanbul's climatic conditions. PV performance was evaluated for different façade orientations (south, east–west, and north) and module tilt angles (70°, 80°, and 90°). Results show that south-facing, 70° tilted systems consistently achieved the highest energy yields and economic performance. For low-consumption households, the 500 W system achieved the shortest payback period of 6.7 years, whereas 1 kW systems performed best for medium- and high-consumption households, with payback periods of 6.3 and 5.7 years, respectively. East–west orientations also performed well, while north-facing systems were least economically viable. These findings suggest that balcony plug-and-play PV systems could offer a practical and cost-effective solution to Türkiye's low residential PV penetration, enabling widespread adoption in multi-story apartments without complex installation or property issues.

Keywords: Residential, Plug-and-play photovoltaics, BEopt, Building energy simulation, Distributed generation

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Received: October 30, 2025
Accepted: January 22, 2026
Published: March 15, 2026

Cite as: Duman, A. C. (2026). Performance assessment of plug-and-play photovoltaic systems in Istanbul. *BSJ Engineering and Science*, *9*(2), 469–479.

1. Introduction

Decentralized renewable energy systems have been growing rapidly as a defining feature of Europe's energy transition. In recent years, especially following the Russia–Ukraine war, rising gas prices and subsequent increases in electricity prices have accelerated this transition across many countries (Sun et al., 2024).

In countries where residential electricity prices have reached exceptionally high levels, households have increasingly turned to small-scale photovoltaic (PV) solutions as a cost-mitigation strategy. Germany represents a prominent example in this context, with residential electricity prices approaching €0.40/kWh in recent years (Eurostat, 2025).

Beyond conventional rooftop PV systems, Germany has experienced a remarkable boom in balcony solar systems (Balkonkraftwerke in German) over the past few years and the number of these systems has reached around one million in the country as of 2025 (PV magazine Energy Storage, 2025). These plug-in PV units enable users to generate their own electricity in a simple and affordable way without the need for rooftop installations (Gögelein et al., 2024). While the feasibility of rooftop PVs has been extensively studied in the literature, this new phenomenon of plug-and-play balcony PV systems has received relatively little attention. This paper, therefore, examines the technical and economic dimensions of balcony PV systems in Türkiye.

1.1. Definition and Characteristics of Plug-and-Play PV Systems

Plug-and-play PV systems are small-scale, modular solar installations designed for direct and simple integration into residential electrical networks without the need for professional installation. Unlike conventional PV systems that require certified installers, complex wiring, and utility approval, plug-and-play systems are equipped with integrated microinverters and standard AC connectors, allowing end users to plug the unit directly into a household socket (230 V AC). Once connected, the system immediately begins feeding the generated electricity into the household circuit, thereby reducing the user's electricity demand from the main grid (Gerber et al., 2025).

Due to their ease of installation and portability, these systems are particularly suited for urban residents, tenants, and users living in small apartments with moderate energy demand, especially those without access to a dedicated rooftop area (Seme et al., 2024).

The rated power output of individual plug-and-play modules generally ranges from 300 Wp to 450 Wp. Although their total capacity is limited compared to traditional rooftop PV systems, they can achieve high self-consumption rates, as most of the generated electricity is used directly within the household. Balcony solar PV plug-and-play system installation examples are shown in Figure 1.

Figure 1. Examples of balcony plug-and-play PV systems.

1.2. Legal and Policy Context in Germany with Comparison to Türkiye

Germany has experienced a remarkable boom in plug-and-play PV systems in recent years. This surge has been driven not only by growing public interest in decentralized energy solutions, but also by a series of targeted policy reforms aimed at reducing administrative barriers and empowering tenants.

Recent policy reforms in Germany, such as simplified registration procedures, an increase in the legal inverter capacity limit from 600 W to 800 W, and tenants' explicit right to install balcony PV systems, have significantly accelerated the adoption of plug-and-play PVs. Installed on balconies, terraces, or façades, these systems enable renters to use their private living space for renewable generation without requiring structural modifications. By doing so, balcony PV allow urban residents, especially tenants who were previously excluded from rooftop PV, to actively participate in the energy transition.

Germany's Solar Package I further accelerated PV deployment by removing bureaucratic barriers and simplifying "system aggregation" under the Renewable Energy Act (EEG) (*Das Solarpaket I Im Überblick*, 2024). Rooftop systems connected to separate grid points are no longer counted as a single installation, and balcony PV systems are fully exempt. For such systems, prior registration with the grid operator is no longer necessary, reporting requirements are minimal, and temporary use of older meters is tolerated. Technical details such as plug type are defined by standards of the German Association for Electrical, Electronic & Information Technologies (VDE/DKE).

While Germany has addressed ownership and administrative barriers through these reforms, Türkiye continues to face challenges in residential PV deployment (Duman & Güler, 2020). Most urban residents live in multi-apartment buildings where rooftops are common property, requiring unanimous owner consent for installation. Consequently, rooftop PV adoption remains limited to detached houses, excluding apartment dwellers from direct participation. The German experience demonstrates how small-scale, plug-and-play PV can democratize solar access. By adapting its regulatory framework to support decentralized systems, Türkiye could enable a broader segment of its population to contribute to the renewable energy transition.

1.3. Literature Review

Research on balcony or plug-and-play PV systems remains relatively limited, as these systems represent a very recent and rapidly emerging phenomenon.

Existing studies largely focus on assessing their technical performance, energy yield, and economic feasibility, particularly in dense urban environments where rooftop installations are constrained. Seme et al. (2024) evaluated the feasibility of 600 W plug-and-play balcony PV systems using 15-minute household load data and locally measured solar radiation. By comparing projected PV generation with actual consumption profiles under high-tariff and low-tariff conditions, the study estimated household-level annual savings and payback times. The results showed that monthly electricity expenditures could be reduced by about 15%, yielding investment payback periods typically between 4 and 9 years, depending on household consumption consistency and tariff levels. Stefanović et al. (2025) evaluated PV panels installed on the façades of high-rise buildings in Serbia using EnergyPlus simulations. The results showed annual electricity savings of 13–58% and payback periods between 8.4 and 12.9 years, demonstrating that vertical and non-rooftop PV applications can be economically viable in dense urban areas with limited rooftop access (an insight that is relevant for balcony PV systems in Türkiye). Taberner Subirats (2025) analyzed plug-and-play PV systems in Ghent, Belgium, where residential electricity prices average 0.30 EUR/kWh, and reported payback periods of 2.8–4.1 years under different self-consumption scenarios. With an investment cost of 870 EUR/kW, the systems achieved average payback times of about 3.2 years based on real household profiles, demonstrating high economic attractiveness in high-tariff markets. Polański et al. (2025) assessed balcony PV potential in Poland's prefabricated large-panel apartment buildings. The study found that approximately 30% of the country's three million balconies are suitable for PV installation. Depending on module efficiency, the potential installed capacity is estimated at around 0.6 GW (equivalent to 2.75% of Poland's total PV capacity in 2025). The study highlighted that optimizing the tilt angle from 90° to 70° for south-facing balconies can increase annual output by over 24%, while also emphasizing that individual estate-level assessments are necessary due to variations in shading and balcony design. The key findings of these studies and their comparative payback periods are presented in Table 1.

Table 1. Economic summary of existing studies

Location	Price (€/kW)	Payback (yr)
Serbia	0.06	8.4 – 12.9
Slovenia	0.22	4 – 9
Belgium	0.30	2.8 – 3.5
Germany	0.40	2 – 3

Beyond technical and economic evaluations, several studies have examined behavioral, socioeconomic, and regulatory factors shaping the adoption and wider diffusion of balcony PV systems. (Gögelein et al., 2024) proposed a method for estimating the azimuth and tilt of balcony PV modules by comparing on-site power data with "Forecast.Solar" predictions. The approach eliminates the need for users to manually input installation parameters, making balcony PV systems more accessible for non-expert users. (Kraschewski et al., 2025) analyzed the adoption patterns of plug-in PV systems using spatial econometric models, identifying socioeconomic and regional factors influencing uptake. The results show that lower upfront costs and renter-friendly installation make plug-in PV systems more accessible to lower-income households and tenants, promoting greater energy inclusivity. (Galvin, 2024) developed a model in which landlords or rental housing companies provide tenants with free balcony PV systems in exchange for up to half of the financial benefits. With an initial investment of around €3,000, landlords could gain over €32,000 in net present value (NPV) within 20 years and more than €250,000 after 36 years. (Molnár & Szép, 2025) examined Hungarian households' intentions to adopt balcony PV systems, finding that perceived benefits, social influence, supportive conditions, and economic value strongly shape adoption intentions. Although awareness and interest were high, the actual adoption of the systems may lag without regulatory clarity and supportive policies.

1.4. Contribution

Balcony and plug-and-play PV systems are a very recent and rapidly expanding phenomenon; for instance, installations in Germany have already exceeded one million units, yet the academic literature remains limited. This gap highlights the need for country-specific analyses, particularly for Türkiye, where high solar potential contrasts with relatively low electricity prices.
This study contributes to the emerging literature by: (1) providing the first techno-economic assessment of balcony PV systems for Turkish residential apartments, (2) evaluating multiple orientations and tilt angles representative of real urban balconies, and (3) examining economic feasibility under varying electricity price scenarios. These contributions aim to fill a gap in current research and offer a basis for future policy and system-design discussions.

2. Materials and Methods

The performance and economic analysis of plug-and-play PV systems in residential apartments were conducted using the BEopt (Building Energy Optimization) software developed by the National Renewable Energy Laboratory (NREL) in the United States. BEopt is a simulation and optimization tool that enables detailed modeling of residential buildings, allowing users to analyze energy consumption, system performance, and cost-effectiveness for various energy efficiency and renewable energy measures (Christensen and Horowitz, 2011). The methodological framework adopted in this study is illustrated in Figure 2 as a flowchart.

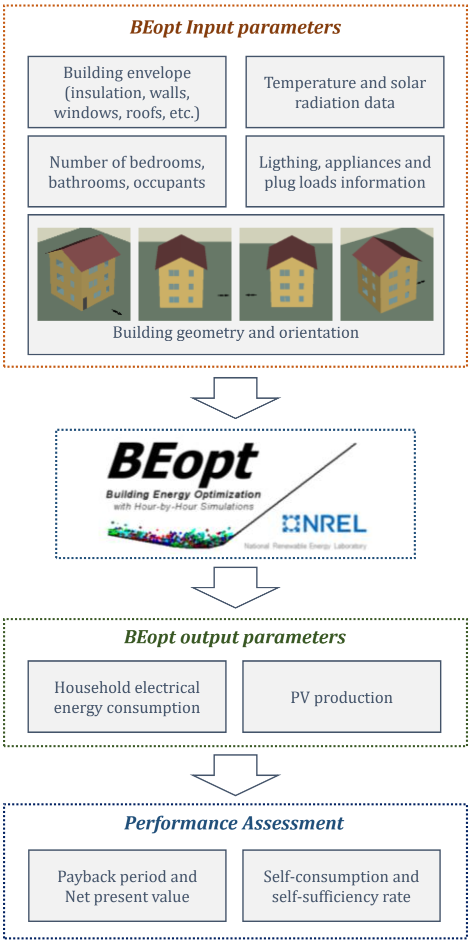


Figure 2. Flowchart of the study.

The workflow begins with collection of meteorological and geographical data, including latitude, longitude, and climate information. These data were obtained from NREL's weather database and used to define the local environmental conditions within BEopt. Subsequently, apartment buildings representative of typical urban dwellings in Istanbul were modeled. The models were configured for households with three and four occupants, reflecting realistic residential characteristics in terms of floor area and number of rooms.
The next stage involved simulating the electricity consumption profiles of these households under standard operating conditions. Once the baseline load

profiles were established, plug-and-play PV systems with nominal capacities of 0.5 kW, 1.0 kW and 1.5 kW were integrated into the apartment models. The simulations were carried out for four distinct building orientations (north-, south-, east-, and west-facing) to capture the effects of solar exposure on system performance and self-sufficiency ratios. Finally, the economic performance of each configuration was assessed by considering current electricity tariffs and plug-and-play system costs in Türkiye. Metrics such as annual energy yield, self-consumption rate, self-sufficiency rate and payback were evaluated to evaluate the performance of the systems for different household types and orientations.

2.1. BEopt Input Data

The building size and architecture is first modeled to simulate the hourly electricity and natural gas demand of a typical concrete apartment unit in Istanbul. The model captures the thermal behavior, HVAC performance, and appliance electricity consumption under realistic operating conditions. The modeling screen of BEopt is shown in Figure 3.

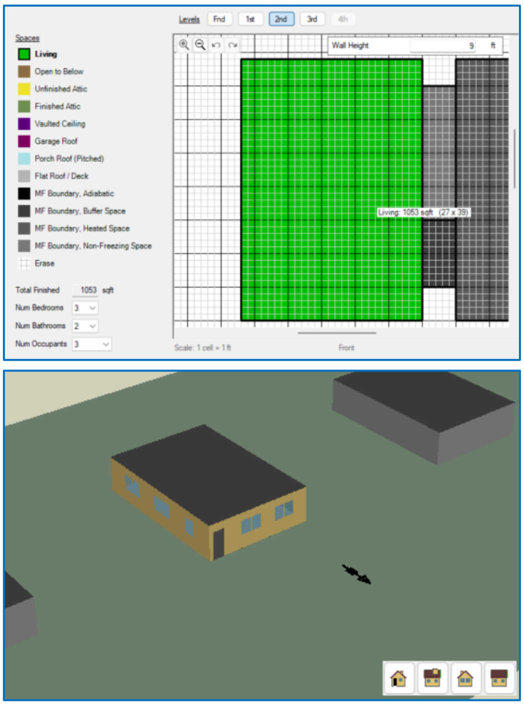


Figure 3. Modeling of a single mid-floor flat of a multi-story apartment building in BEopt.

2.1.1. Building geometry and envelope

The building is modeled as a dwelling unit with adjacent buildings located 10 ft on each side, reflecting an urban apartment configuration. The exterior walls consist of 6-inch concrete masonry units (CMU) filled with concrete and insulated externally with R-10 extruded polystyrene (XPS), while the outer surface is finished with light-colored vinyl siding. The roof assembly features an unfinished attic with R-19 fiberglass insulation and a medium-colored tile roof. The foundation is a slab-on-grade construction with R-10 XPS insulation extending 2 ft below grade, and 80% of the interior floor area is covered with carpet. All walls and ceilings are lined with ½-inch drywall, while interior partitions are constructed from the same material, ensuring consistent thermal mass representation throughout the building.

Fenestration is evenly distributed on all four façades, with 15% window-to-wall ratio per orientation. Windows are modeled as double-pane, Low-E, argon-filled, non-metal frame, medium-gain glazing systems, providing balanced thermal and solar performance. Seasonal interior shading coefficients of 0.7 are applied for both summer and winter to account for blinds or curtains typically used in residential settings. Exterior doors are modeled as fiberglass with a total area of 20 ft^2, and 2-ft eaves are included to represent realistic shading from the roof overhang.

Infiltration is set at 5 ACH50, representing moderate air-tightness typical of newer multifamily concrete structures. Natural ventilation is activated only during the cooling months, operating seven days per week to reflect window-opening behavior in summer. Building envelope input data is shared in Table 2.

Table 2. Building envelope parameters

Parameter	Option
Building	
Orientation	North
Neighbors	Left/Right at 20 ft
Walls	
Concrete Masonry	6-in Concrete Filled
Wall Sheating	R-10 XPS
Exterior Finish	Vinyl Light
Ceiling/Roofs	
Unfinished Attic	Ceiling R-19 Fiberglass, Vented
Roof Material	Tile, Medium
Foundation/Floors	
Slab	2 ft R10 XPS
Carpet	80%
Thermal Mass	
Floor Mass	Wood Surface
Exterior Wall Mass	1/2 in. Drywall
Partitio Wall Mass	1/2 in. Drywall
Ceiling Mass	1/2 in. Drywall
Windows & Doors	
Window Areas	F15 B15 L15 R15
Windows	Low-E, Double, Non-metal, Arg, M-Gain
Interior Shading	Summer = 0.7, Winter = 0.7
Door Area	20 ft^2
Doors	Fiberglass
Eaves	2 ft
Airflow	
Air Leakage	5 ACH50
Mech. Ventilation	None
Natural Ventilation	Cooling Months Only, 7 days/week

2.1.2. Appliances, lighting and plug loads

The space conditioning system consists of a central air conditioner with a SEER2 rating of 13.4 and a 90% AFUE gas furnace, representing a standard-efficiency mixed HVAC setup. Heating and cooling operation schedules are defined seasonally, with heating enabled from September through April and cooling from March through October. The thermostat setpoints are 71 °F for heating and 76 °F for cooling, consistent with residential comfort standards.

Domestic hot water is supplied by a gas-fired storage water heater with a Uniform Energy Factor (UEF) of 0.66. Hot water is distributed through uninsulated copper piping, reflecting typical installation practices in existing buildings. The fixture flow multiplier of 1.0, corresponds to standard water use patterns.

All interior lighting is modeled as 100% LED, representing high-efficiency lighting technology now standard in modern dwellings.

Major appliances include a top-freezer refrigerator with an energy factor of 17.6, an electric cooking range, a standard dishwasher, a standard clothes washer, and an electric clothes dryer.

These parameters reflect typical mid-efficiency appliances found in Turkish households. Appliances and plug loads data is shared in Table 3.

Table 3. Ligthing, appliances and plug loads parameters

Parameter	Option
Space Conditioning	
Central Air Conditioner	SEER2 16.2**, None*
Furnace	Gas, 90%, AFUE
Heating/Cooling Sessions	Heating Sep-Apr, Cooling Mar-Oct
Cooling Set Point	76 F
Heating Set Point	71 F
Water Heating	
Water Heater	Gas, Tank, UEF=0.83
Distribution	Uninsulated, Copper
Lighting	
LED Lighting	100%
Appliances & Fixtures	
Refrigerator	Top freezer, EF = 21.9
Cooking Range	Electric
Dishwasher	270 kWh
Clothes Washer	152 kWh
Clothes Dryer	Electric
Hot Water Fixtures	1.00
Appliances & Fixtures Schedules	
Refrigerator Schedule	Standard
Cooking Range Schedule	Standard
Clothes Dryer Schedule	Standard
Miscellaneous	
Plug Loads	0.50**, 0.25*
Miscellaneous Schedules	
Plug Loads Schedule	Standard

**high and medium consumption, *low consumption

2.1.3. Climatic data and solar radiation

The climatic and solar radiation data are extracted directly from the BEopt software database, which provides location-specific hourly weather profiles. Ambient temperature primarily influences the heating and cooling loads of the modeled apartment units, while solar radiation data are used to estimate the PV power output. Based on these climatic parameters, the hourly power generation of 0.5 kW, 1.0 kW and 1.5 kW balcony plug-and-play PV systems was simulated within BEopt.

Figure 4 presents the resulting PV power output profiles for systems oriented toward the south, north, east, and west façades. Additionally, different tilt angles (90°, 80°, and 70°) were considered to assess their impact on overall energy generation performance. The annual PV power outputs for south-facing systems were 487 kWh, 431 kWh, and 367 kWh for tilt angles of 70°, 80°, and 90°, respectively. For east- and west-facing systems, the corresponding values were 365.45 kWh, 327.89 kWh, and 290.59 kWh, while north-facing systems generated 206.24 kWh, 187.85 kWh, and 174.75 kWh. The results indicate that south-facing balcony PVs achieve the highest annual energy yield, whereas north-facing systems produce less than half of that amount. Although east- and west-facing systems produce lower annual energy than south-facing ones, their generation peaks during the summer months, coinciding with periods of high air conditioning demand.

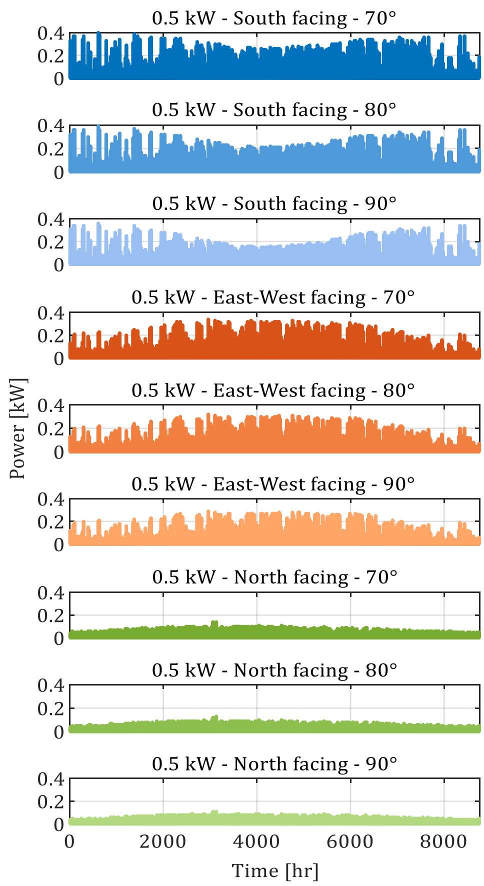


Figure 4. PV power output for different orientations and tilt angles.

2.1.4. Electrical load profiles of low-, medium- and high-consumption households

The electrical load profiles of the three households with low, medium, and high electricity consumption are presented in Figure 5, while their total annual energy usages are shown in Figure 6.

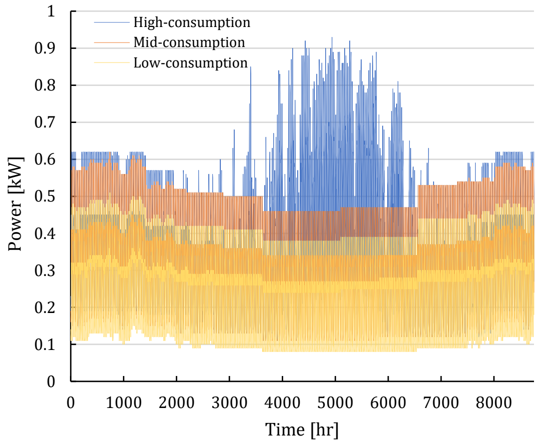


Figure 5. Annual electrical load profiles of households.

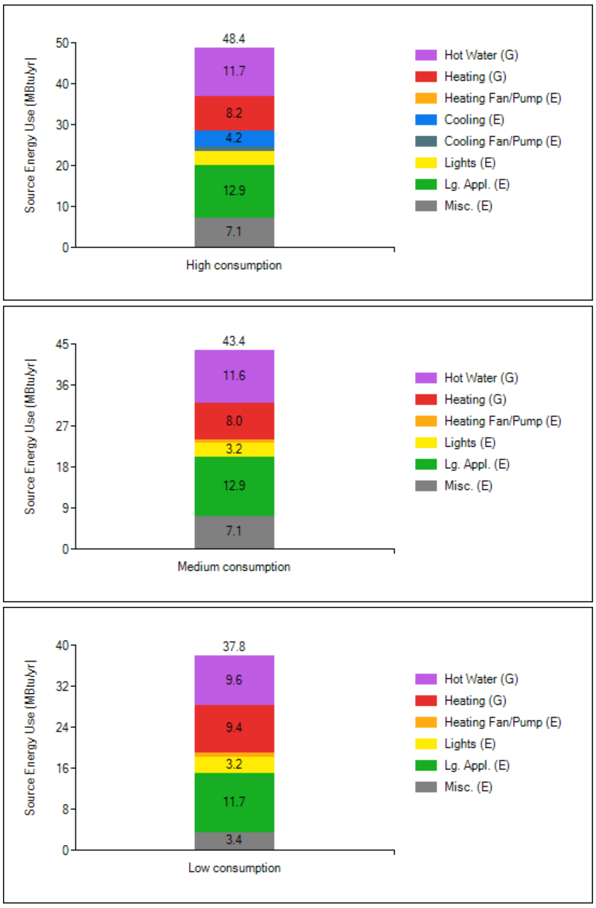


Figure 6. Detailed breakdown of total household energy consumption based on BEopt simulations.

The apartment units modeled in this study represent mid-floor dwellings, excluding ground- and top-floor cases to avoid thermal boundary effects and ensure general representativeness of typical urban apartments. The low-consumption household corresponds to a 98 m^2 apartment with two rooms and one bathroom, whereas the medium- and high-consumption households represent a 120 m^2 apartment with three rooms and two bathrooms. The high-consumption household includes an air conditioner, while the others do not. All layouts were simulated under identical climatic and internal gain conditions to assess the impact of occupancy level on annual energy consumption. The resulting annual electricity demands were 2148 kWh, 2703 kWh, and 3244 kWh for the low-, medium-, and high-electricity consumption households, respectively.

2.2. Economic Data

The economic evaluation of balcony plug-and-play PV systems was conducted based on current market prices in Türkiye. The initial investment cost was assumed to be 247 USD for a 500 W system, 437 USD for a 1000 W system, and 674 USD for a 1500 W system (Maxxisun, 2025). These costs include the microinverter, cabling, and balcony-mounting equipment, representing the total upfront expense for each configuration. The annual operation and maintenance (O&M) cost was set at 10 USD-year.

A flat electricity tariff of 0.104 USD/kWh was adopted to represent the average residential rate in Türkiye. The real interest rate was taken as 2%, and the system lifetime was assumed to be 20 years for economic calculations.

It was further assumed that no electricity is sold back to the grid, and no battery storage is included in the system. The economic benefit is derived solely from the avoided cost of purchased grid electricity. This framework allows the assessment of payback period and NPV based purely on self-consumption potential and system size. In addition to economic indicators, system performance was also evaluated using the self-consumption rate (SCR) and self-sufficiency rate (SSR), which quantify how effectively the PV electricity is utilized within the household and the extent to which the household's electricity demand is met by on-site generation.

2.3. Performance Assessment

The economic assessment of the balcony plug-and-play PV systems was conducted based on the fundamental indicators of annual savings, net present value (NPV), and discounted payback period (DPP). The annual cost saving resulting from PV self-consumption is expressed as in equation 1:

$$S_{ann} = \sum_{t=1}^{8760} \min(L_t, P_t) \times \lambda_t \quad (1)$$

where L_t represents the hourly household electricity demand (kWh), P_t denotes the hourly PV power generation (kWh), and λ_t is the unit electricity price (USD/kWh). This formulation quantifies the total monetary value of electricity that would otherwise be purchased from the grid but is instead supplied by the PV system.

The NPV of the investment is then calculated as in equation 2:

$$NPV = -I_0 + \sum_{n=1}^{N} \frac{S_{ann} - C_{om}}{(1+r)^n} \quad (2)$$

where I_0 is the initial investment cost (USD), C_{om} is the annual operation and maintenance cost (USD/year), r is the real discount rate, and N is the system lifetime (years).

The discounted payback period (DPP) (equation 3) is defined as the year when the cumulative discounted cash flows equal the initial investment.

$$I_0 = \sum_{n=1}^{DPP} \frac{S_{ann} - C_{om}}{(1+r)^n} \quad (3)$$

This expression identifies the number of years required for the project's discounted revenues to offset its initial cost.

In addition to these financial indicators, the self-consumption rate (equation 4) and self-sufficiency rate were calculated to evaluate the share of PV electricity utilized within the dwelling:

$$SCR = \frac{\sum_{t=1}^{8760} \min(L_t, P_t)}{\sum_{t=1}^{8760} P_t} \times 100 \quad (4)$$

where the numerator represents the total self-consumed PV energy and the denominator the total annual PV generation. The SCR indicates how efficiently the household utilizes the locally produced PV electricity; higher values imply greater alignment between the load and PV generation profiles.

Similarly, the SSR (equation 5) was calculated to assess the extent to which the household's electricity demand can be met by on-site PV generation:

$$SSR = \frac{\sum_{t=1}^{8760} \min(L_t, P_t)}{\sum_{t=1}^{8760} L_t} \times 100 \quad (5)$$

where the numerator represents the PV energy directly consumed within the dwelling, and the denominator corresponds to the total annual electricity demand. The SSR reflects the degree of energy independence from the grid; higher values indicate a greater share of the load being supplied by PV rather than grid electricity.

3. Results

The performance analysis of plug-and-play PV systems considers low-, medium-, and high-electricity consumption apartments, evaluating system performance across multiple orientations (south, east–west, and north) and tilt angles (70°, 80°, and 90°). Key performance indicators include the DPP, NPV, SCR, and SSR.

3.1. Performance for High-Consumption Households (270 kWh/month)

Table 4 presents the techno-economic and energy performance indicators of plug-and-play PV systems for high-consumption households in Istanbul. South-facing configurations yield the highest overall performance across all tilt angles and system capacities. The 1 kW system tilted at 70° achieves the shortest DPP of 5.7 years, with a NPV of 908 USD, indicating strong economic feasibility. The 1.5 kW system tilted at 70° achieves the highest NPV of 1096 USD. Although increasing the tilt angle to 90° slightly decreases annual generation and worsens the DPP, the south-facing systems maintain a clear advantage in both profitability and SSR, which reaches up to 35% for the 1.5 kW configuration. East–West oriented systems also perform competitively, offering an attractive balance between self-consumption and return on investment. For instance, the 1 kW East–West system at 70° achieves a DPP of 7.7 years and an NPV of 571 USD, which is roughly 30% longer payback compared to the best south-facing case. North-facing systems demonstrate limited economic viability, with all 500 W cases failing to achieve payback within 20 years and negative NPVs. Even larger capacities (1–1.5 kW) show DPPs above 14 years, confirming that north orientation remains unsuitable for economic plug-and-play PV deployment in Istanbul.

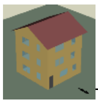
Table 4. Results for high-consumption households (4-person household with air conditioner: 270 kWh/mo)

Facing	PV (W)	Tilt (°)	DPP (yr)	NPV ($)	SCR (%)	SSR (%)
South 	500	70	6.5	420	100	15
		80	7.7	325	100	13
		90	9.7	216	100	11
	1000	70	5.7	908	91	27
		80	6.4	763	93	25
		90	7.6	584	95	21
	1500	70	6.7	1096	78	35
		80	7.3	959	81	32
		90	8.4	761	85	29
East-West 	500	70	9.8	213	100	11
		80	11.5	149	100	10
		90	14	85	100	9
	1000	70	7.7	571	94	21
		80	8.7	466	95	19
		90	10.0	360	97	17
	1500	70	8.8	704	82	27
		80	9.7	591	85	26
		90	10.7	477	88	24
North 	500	70	>20	-59	100	6.4
		80	>20	-90	100	5.8
		90	>20	-112	100	5.4
	1000	70	15.5	103	100	13
		80	17.9	40	100	12
		90	>20	-4	100	11
	1500	70	14.3	217	100	19
		80	16.3	124	100	17
		90	18.1	56	100	16

3.2. Performance for Medium-Consumption Households (225 kWh/month)

Table 5 summarizes the results for medium-consumption households. South-facing systems demonstrate the most favorable combination of financial and energy performance. The 1 kW system tilted at 70° achieves the shortest DPP of 6.3 years, whereas the 1.5 kW system achieves the highest NPV of 816 USD. The SSR reaches 36% for the 1.5 kW configuration, indicating substantial coverage of household demand via PV electricity. East–West systems show moderately lower NPVs and longer DPPs but still offer strong self-consumption levels (88–100%), with the 1 kW, 70° system reaching a DPP of 8.4 years and an NPV of 496 USD. These systems remain technically attractive alternatives for buildings with limited southern exposure.

Table 5. Results for mid-consumption households (4-person household without air conditioner: 225 kWh/mo)

Facing	PV (W)	Tilt (°)	DPP (yr)	NPV ($)	SCR (%)	SSR (%)
South 	500	70	6.5	420	100	18
		80	7.7	325	100	16
		90	1.9	215	100	14
	1000	70	6.3	777	83	30
		80	6.9	686	87	28
		90	7.9	554	92	25
	1500	70	8.1	816	66	36
		80	8.6	735	71	34
		90	9.4	627	78	32
East-West 	500	70	9.8	212	100	14
		80	11.5	149	100	12
		90	14.1	85	100	11
	1000	70	8.4	496	88	24
		80	9.3	411	90	22
		90	10.5	325	93	21
	1500	70	9.9	559	75	30
		80	10.7	476	78	29
		90	11.7	390	83	27
North 	500	70	>20	-59	100	8
		80	>20	-90	100	7
		90	>20	-112	100	6
	1000	70	15.5	103	100	15
		80	18.0	40	100	14
		90	>20	-4	100	13
	1500	70	14.3	217	100	23
		80	16.3	124	100	21
		90	18.1	57	100	19

3.3. Performance for Low-Consumption Households (179 kWh/month)

Table 6 presents the economic and energy performance of plug-and-play PV systems for low-consumption households. The 500 W system tilted at 70° achieves the lowest DPP of 6.7 years. The NPV is found to be 403 USD. The 1 kW system provides the highest NPV of 622 USD. East–West systems deliver stable and technically acceptable performance, featuring nearly complete self-consumption and moderate profitability. For instance, the 1 kW, 70° configuration provides a DPP of 9.4 years and an NPV of 405 USD, making it a relatively viable alternative with a payback period below 10 years where south orientation is unavailable. North-facing arrays remain uneconomical for all configurations. No 500 W case achieves payback within 20 years, and NPVs remain negative. Even larger systems (1–1.5 kW) exhibit DPP values above 14 years.

Table 6. Results for low-consumption households (3-person household without air conditioner: 179 kWh/mo)

Facing	PV (W)	Tilt (°)	DPP (yr)	NPV ($)	SCR (%)	SSR (%)
South 	500	70	6.7	403	98	22
		80	7.8	318	99	20
		90	9.7	213	100	17
	1000	70	7.3	622	74	34
		80	7.9	553	78	31
		90	8.8	460	85	29
	1500	70	9.7	584	57	39
		80	10.2	530	62	37
		90	11.0	450	69	35
East-West 	500	70	10.0	205	99	17
		80	11.7	145	99	15
		90	14.1	85	100	14
	1000	70	9.4	405	81	27
		80	10.3	339	84	26
		90	11.5	267	88	24
	1500	70	11.5	408	67	34
		80	12.2	354	71	33
		90	13.0	294	76	31
North 	500	70	>20	-59	100	10
		80	>20	-90	100	9
		90	>20	-112	100	8
	1000	70	15.5	103	100	19
		80	17.8	40	100	17
		90	>20	-5	100	16
	1500	70	14.5	208	100	29
		80	16.3	122	100	26
		90	18.1	56	100	24

3.4. Environmental Contribution

The environmental benefits of plug-and-play PV systems were quantified in terms of annual CO_2 emission reductions using a grid emission factor of 0.442 kg CO_2/kWh, representing the average value for Türkiye's electricity mix, and based on PV self-sufficiency as expressed in equation 6:

$$CO_{2,savings} = E_{PV,self} \times EF_{grid} \quad (6)$$

where $E_{PV,self}$ is the annual amount of PV-generated electricity directly consumed within the household and EF_{grid} is the grid emission factor.

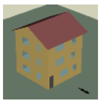
The annual PV-based self-sufficiency was obtained as in equation 7:

$$E_{PV,self} = E_{load,year} \times \frac{SSR}{100} \quad (7)$$

where $E_{load,year}$ is the annual household electricity demand and *SSR* is the self-sufficiency ratio.

Table 7 presents the estimated CO_2 savings across different system capacities, orientations, and household consumption levels. As expected, south-facing systems yield the highest reductions, reaching approximately 500 kg CO_2 per year for 1.5 kW configurations. East–West systems also deliver meaningful savings, typically in the range of 300–380 kg CO_2 per year for the largest system sizes, owing to their high self-consumption ratios. In contrast, north-facing systems provide considerably lower reductions, generally below 300 kg CO_2 per year, reflecting their limited generation potential under Türkiye's solar conditions.

Table 7. Estimated annual CO_2 savings of balcony PV systems (kg CO_2/yr)

Facing	PV (W)	Tilt (°)	Consumption (kWh/mo)		
			270	225	179
South 	500	70	215	215	209
		80	186	191	190
		90	158	167	161
	1000	70	387	358	323
		80	358	334	294
		90	301	298	275
	1500	70	501	430	370
		80	458	406	351
		90	415	382	332
East-West 	500	70	158	167	161
		80	143	143	142
		90	129	131	133
	1000	70	301	286	256
		80	272	263	247
		90	243	250	228
	1500	70	387	358	323
		80	372	346	313
		90	344	322	294
North 	500	70	86	95	95
		80	86	84	85
		90	72	72	76
	1000	70	186	179	180
		80	172	167	161
		90	158	155	152
	1500	70	272	274	275
		80	243	251	247
		90	229	227	228

3.5. Sensitivity Analysis

To assess how electricity prices influence the economic feasibility of plug-and-play PV systems, a sensitivity analysis was performed for the high-consumption household (270 kWh/month) using a 1 kW south-facing array tilted at 70°. Four alternative tariff scenarios were examined by increasing the base electricity price by 50%, 100%, 150%, and 200%. Considering that Türkiye currently has one of the lowest residential electricity tariffs in Europe, these higher price levels can be viewed as representative of tariff conditions in many southern European countries, where electricity prices are typically higher and PV potential is comparable. Moreover, because residential electricity tariffs in Türkiye remain partially subsidized, future increases are likely, meaning that higher-price scenarios may also reflect potential long-term domestic conditions rather than purely international comparisons. Table 8 summarizes the resulting DPP values for south-, east–west-, and north-facing orientations.

Table 8. Sensitivity of DPP to electricity price variations (270 kWh/mo house, 1 kW south-facing PV tilted at 70°)

Price ($/kWh)	DPP (yr)		
	South	East-West	North
0.104	5.7	7.7	15.5
0.156	3.6	4.8	8.9
0.208	2.6	3.4	6.2
0.260	2.1	2.7	4.8

As retail electricity prices increase, the economic performance of small plug-and-play systems improves sharply. For south-facing systems, the DPP declines from 5.7 years at the base tariff of 0.104 USD/kWh to 3.6 years when prices rise by 50%. East–west configurations show a similar trend, reaching a DPP of 4.8 years under the same price increase. Notably, even north-facing systems, normally the least favorable option due to their limited solar exposure, benefit substantially from higher tariffs: at a 50% price increase, the DPP falls below 9 years, demonstrating that such systems can become economically viable in Türkiye's evolving electricity market. The results illustrate that rising retail tariffs and ongoing tariff reforms can enhance the attractiveness of plug-and-play PV, even in suboptimal orientations.

4. Discussion

Plug-and-play PV systems have gained remarkable traction across Europe in recent years, particularly in Germany, where more than one million units are now in operation. The surge is attributable not only to elevated retail electricity prices, driven by geopolitical instability following the Russia–Ukraine conflict, but also to targeted policy interventions that removed administrative barriers and empowered tenants. Compared to traditional rooftop installations, plug-and-play systems offer substantially lower upfront costs, simplified installation, and minimal bureaucratic requirements, resulting in payback periods as short as three years in high-tariff markets such as Germany. These developments illustrate how regulatory frameworks can significantly influence the diffusion of small-scale PV technologies.

In the Turkish context, the findings of this study show that plug-and-play PV systems can also provide attractive economic returns despite substantially lower electricity prices, which naturally limit the magnitude of bill savings. South-facing households achieve payback periods of approximately 5–6 years, while east–west orientations fall within the 7–9 year range. Even north-facing dwellings, although less favorable, exhibit payback periods of around 14 years, indicating that the use of plug-and-play systems is not strictly limited to optimal solar exposures, particularly under scenarios of rising electricity tariffs. The analysis further shows that the tilt angle has a meaningful but manageable impact. Although a 70° tilt consistently yields the highest annual energy output, the more common balcony angles of 80–90° still provide viable economic performance.

An important factor shaping these outcomes is the structure of the Turkish residential building stock. Most urban residents live in multi-story apartment blocks, where rooftop PV installations are constrained by collective ownership and the requirement for unanimous approval among residents. Plug-and-play systems therefore present a promising alternative that democratizes access to solar energy by enabling installation without structural alterations or formal permitting. The results imply that such systems could stimulate a similar adoption trend in Türkiye as seen in Germany, and this potential could be further strengthened through an enabling regulatory environment.

The sensitivity analysis further underscores the importance of electricity pricing in shaping financial outcomes. When tariffs increase by 50%, payback periods decline dramatically to 3.6 years for south-facing dwellings and 4.8 years for east–west orientations. Even north-facing units become economically viable with payback times below nine years. Given that Türkiye's residential tariffs are among the lowest in Europe and partially subsidized, future price increases are plausible. This suggests that the long-term economic attractiveness of plug-and-play PV systems may be even greater than indicated by baseline results.

A cross-country comparison with existing studies (Table 1) contextualizes the findings within the broader literature. In high-tariff markets such as Belgium and Germany (0.30–0.40 €/kWh), payback periods range from 2 to 4 years. In moderate-tariff regions like Slovenia (0.22 €/kWh), paybacks extend to 4–9 years. In Serbia, where tariffs are very low (0.062 €/kWh), façade-mounted systems show payback periods exceeding eight years. These outcomes confirm that electricity prices, rather than solar irradiance, are the dominant determinant of economic feasibility. Türkiye, which combines high solar resource availability with low electricity prices (~0.10 USD/kWh), therefore displays intermediate results (5–14 years), fully consistent with international observations.

5. Conclusion

This study evaluated the performance and economic feasibility of balcony plug-and-play PV systems for typical residential apartments in Istanbul, Türkiye, taking into account different household sizes, electricity consumption profiles, and apartment layouts. Building energy simulations were used to estimate the annual electricity demand of low-, medium-, and high-consumption households under Istanbul's climatic and solar radiation conditions. Based on these consumption profiles, the performance of various system capacities, orientations, and tilt angles was assessed to determine their energy output and economic viability. The results indicate that:

- For a low-consumption household (179 kWh/month), a 0.5 kW system achieved the shortest payback period of 6.7 years.
- Medium-consumption households (225 kWh/month) achieved the shortest payback period with a 1 kW system, yielding 6.3 years.
- High-consumption households (270 kWh/month) with an air conditioner achieved a payback period of 5.7 years using a 1 kW system.
- A tilt angle of 70° yielded the best results, but even at 90° (a common angle for balcony installations) systems still performed well.
- East- or west-facing apartments also demonstrated favorable performance, with payback periods between 7 and 9 years, showing that optimal orientation is beneficial but not essential.
- The sensitivity analysis shows that if Türkiye's partially subsidized electricity prices increase toward EU levels, payback periods could shorten markedly, approaching the 3-year range observed in Germany.

Although Türkiye benefits from high solar irradiance, relatively low electricity prices limit financial savings compared to European countries with higher electricity costs. Nevertheless, the sensitivity analysis indicates that increases in retail electricity tariffs would significantly enhance feasibility, making plug-and-play PV systems even more attractive over time. The results highlight the strong potential of balcony PV systems to expand residential solar adoption in Türkiye and suggest that similar assessments should be conducted for other countries to evaluate their suitability under different energy market conditions.

Author Contributions

The percentages of the author' contributions are presented below. The author reviewed and approved the final version of the manuscript.

	A.C.D.
C	100
D	100
S	100
DCP	100
DAI	100
L	100
W	100
SR	100

C= concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision.

Conflict of Interest

The author declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans.

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