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A Life-Cycle Cost Analysis on Photovoltaic (PV) Modules for Türkiye: The Case of Eskisehir's Solar Market Transactions

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Abstract

Solar energy systems have increasingly replaced conventional energy systems, driving global efforts to combat climate change and promote sustainability. This study conducts a comprehensive life-cycle cost analysis (LCCA) of photovoltaic (PV) modules, with a focus on the solar market in Eskisehir, Türkiye. Unlike prior research, this work integrates financial analysis with ecological benefits, offering a localized case study. By leveraging primary data from surveys and government sources, the analyses display that investing in PV equipment generates €883.75 in Net Present Value (NPV) savings through the business-as-usual scenario (−€392 under the worst-case and €2350 under the optimistic scenarios) over a 30-year lifespan, demonstrating the financial viability of these systems. Despite high initial costs, PV modules provide ecological and economic advantages that outweigh maintenance expenses, making them a viable solution for reducing fossil fuel dependence. The findings serve as a guideline for decision-makers, consumers, and producers to foster a sustainable solar energy market in Türkiye and similar developing economies by enabling feasible PV investments through appropriate Feed-in tariff mechanisms.

Keywords: life-cycle cost analysis; consumers; PV modules; solar energy markets; net present value; Feed-in tariff

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1. Introduction

The mainstream influence shaping countries in competitive energy markets is a functioning economy supported by science and innovation, which collectively influences and reshapes energy production and consumption habits through the effective use of renewable energy [1], as well as transmission, telecommunication, and information (i.e., artificial intelligence) technologies [2,3]. As a result, this phenomenon compels countries and Türkiye to reconsider their energy agenda to position themselves within the global energy platform by focusing on affordability, energy security, and decarbonization [4,5]. Governments are responsible for improving citizens' living standards by implementing necessary arrangements, legislation, and adaptations. In doing so, they explore global interactions, leverage know-how, and draw insights from scientific research. While over 1.3 billion individuals worldwide still lack access to electricity [6], developing countries can utilize renewable energy in alignment with their geographic and institutional capabilities. This shift can create jobs, reduce trade deficits, and balance energy deficits by cutting energy imports, as seen in Türkiye. Türkiye's strategic geographic location is a crucial priority for regional cooperation [7], with significant potential for renewable energy sources, such as solar [8]. In particular, solar PV technology has seen growing adoption [9–11], deployment [12], and importance in both developed and developing countries [13–15]. Achieving a sustainable energy transition requires effective governmental management and strategic planning to secure a cleaner future [16].

The economic aspects and government policies (specifically, the Feed-in Tariffs (FiTs) policy for Türkiye, as elaborated in detail in reference [8]) concerning renewable energy in Türkiye are discussed in reference [17]. Developments in renewable energy legislation have accelerated growth in the country and expanded investment alternatives in the field. However, the effectiveness of these economic instruments has been increasingly challenged by policy inconsistencies and regulatory barriers. While these limitations have slowed broader adoption of renewable energy technologies, significant progress has nonetheless been achieved in the solar energy sector. Statistical data illustrate a notable shift in Türkiye's energy landscape: as of 2013, the country had no installed solar energy capacity, yet this figure rose sharply to 6.667 GW by 2020 [18] and reached 11.3 GW in 2023, representing a 20% year-on-year increase from 2022, demonstrating the rapid expansion of solar technology.

Global interest in renewable energy technologies continues to grow, and solar energy systems, in particular, have become central to the energy transition due to declining costs and ongoing technological advancements. In recent years, a substantial increase in photovoltaic (PV) manufacturing capacity has been observed. According to reports published by international organizations, global solar power manufacturing capacity was expected to exceed 1100 GW by the end of 2024; however, as final official data have not yet been fully released, these figures should be regarded as estimates [19]. This upward trend highlights the increasing economic and environmental significance of solar energy and reinforces the relevance of the analyses presented in this study.

This transformation underscores the importance of renewable energy legislation in driving the transition from fossil fuels to renewable sources, motivated by the need to reduce greenhouse gas emissions, enhance energy security, and achieve long-term economic benefits. In this context, a life-cycle cost analysis of producing and consuming energy through local resources (i.e., renewable energy, "solar energy") is conducted in this study with a particular focus on one of Türkiye's cities: Eskisehir. Eskisehir is located in Central Anatolia at an elevation of 788 m and has a continental climate with cold winters and hot, dry summers. The average annual global horizontal irradiation (GHI) is approximately 1550–1600 kWh/m^2/year, which is slightly higher than the national average. These climatic conditions provide a favorable environment for PV electricity generation and enhance the accuracy of long-term savings estimates. The inclusion of these geographical indicators enables comparison with other Turkish regions or international locations with similar solar potentials.

This analysis evaluates the rationality of consumers' energy consumption preferences and tests various decision-making scenarios to enhance resource efficiency in competitive energy markets. Additionally, the study introduces current active renewable energy policies and provides a detailed examination of those implemented in Türkiye. Financial analyses are conducted based on Eskisehir's current economic conditions and Türkiye's active renewable energy policies. The effective implementation of these policies is closely tied to Türkiye's level of development, and as national development progresses, the likelihood of successfully adopting and sustaining both new and existing policies is expected to increase.

Transitioning from conventional fossil-fuel-based energy systems to solar energy systems is a necessary choice for consumers and aligns with the global environmental protection measures emphasized in this study. In line with this rationale, reference [20] notes that transitioning from conventional to non-conventional energy sources is essential in today's world. Solar energy systems can significantly reduce fuel expenditures, particularly when using PV modules [21]. However, a fundamental principle concerns these systems and their acceptance and adaptation in practical life. This principle can be explained in economic terms: although PV systems have operating costs, their most substantial burden is the high initial costs. Thus, the economic rationale behind adopting these systems, and the basis of a rational consumer decision, is that the value of reduced bills or saved energy should exceed the total initial and operational costs over the system's life cycle.

This choice represents a long-term investment strategy and can be justified by economic principles of the time value of money. According to this study, achieving the status of a developed country, such as ensuring energy self-sufficiency, maintaining a clean environment, producing and using advanced technologies, and achieving lower unemployment rates through qualified labor, depends strongly on such strategic decisions. At the global level, these strategies are promoted and supported by international organizations such as the Renewable Energy Policy Network for the 21st Century (REN21) and the International Energy Agency (IEA), which facilitate a rapid transition to solar energy through knowledge exchange and policy development [22].

This study implements an economic inquiry into PV modules. Solar energy directly produces electrical energy with PV modules. For a consensus on a crucial matter, the term "PV module" (i.e., the terminological definition in the study [23]) is used to refer to the combination of both modules and the platform on which they are mounted. Along with that explanation, the study aims to produce an economic analysis of 30 years (there are studies, i.e., [24,25], which take the lifetime of PV modules as 30 years, like our approach) of producing PV modules, serving them to consumers in the Eskisehir economy, and evaluating their contribution to the city and country. If these contributions are rational and significant, starting to produce PV modules in different Turkish cities will allow consumers the choice of cheaper, environmentally friendly, clean, and secure energy systems. This study takes a regional approach to demonstrate that it is viable for the social welfare of a developing country to remain within the main agenda by producing electricity with PV modules. Throughout the process of making these events possible, this study aims to serve as a guideline for all consumers, producers, and stakeholders, outlining which cases the government should prioritize to achieve practical outcomes from this development strategy. The demographic characteristics of Eskisehir, the currently used fuel in the city, and its total consumption, along with expenses, income tax savings, property taxes, mortgage payments, maintenance and insurance, parasitic energy costs, and initial investment costs, are considered in this economic plan.

The PV system analyzed in this study consists of mono-crystalline silicon photovoltaic modules with an average module efficiency of 20.4%, which is representative of the 2023–2024 Turkish residential PV market. The module temperature coefficient is $-0.36\%/^{\circ}C$, and the overall system performance ratio (PR) is assumed to be 0.80, accounting for inverter losses, temperature effects, shading, soiling, and wiring losses. The system includes a high-efficiency string inverter with a nominal efficiency of 97%, mounted using aluminum rails and standard rooftop mounting hardware. The DC system capacity is 3 kW, with AC capacity adjusted through the inverter to match residential consumption and grid export requirements. All specifications were selected to reflect current market conditions and installation practices in Türkiye.

There are several methodological similarities between this study's approach and the literature referenced in [26–31]. However, this work distinguishes itself from those studies by contributing to the growing body of research on photovoltaic (PV) systems through a region-specific life-cycle cost analysis (LCCA) tailored to the economic and environmental context of Eskisehir, Türkiye. While prior research, such as [32], has focused on performance and degradation predictions for PV systems in other regions, this study uniquely integrates financial analysis with ecological impacts. The use of primary data collected from Eskisehir households through an original 2013 survey, combined with secondary data from Turkish governmental institutions such as TurkStat and CBRT in 2024, provides a comprehensive understanding of PV adoption barriers and opportunities in developing countries.

Unlike global-level analyses or case studies conducted in high-income economies, this research highlights the practical implications of transitioning to renewable energy in an emerging economy. It aligns with the Sustainable Development Goals by demonstrating the economic viability of PV systems and their potential to mitigate climate change. Furthermore, the study addresses a critical gap in the literature by combining localized data with a long-term financial evaluation, thereby offering actionable insights for policymakers, consumers, and producers in Türkiye and comparable contexts.

Unlike earlier works such as [21] on solar engineering and [24] on energy payback time, this study expands the scope of LCCAs by incorporating financial scenarios tailored to Türkiye's economic policy environment. The results underscore the importance of policy interventions, such as Feed-in Tariffs, tax incentives, and localized production, to ensure the sustainable adoption of PV technology. Furthermore, while previous works have examined PV system economics or regional solar potential in Turkey, none have combined localized hourly irradiance data for Eskisehir with a 30-year life-cycle cost analysis, degradation-adjusted yield modeling, and multi-scenario policy evaluation. Additionally, earlier studies have not quantified CO_2-emission reductions within an economic framework for residential PV systems in this region. These distinctions clarify the novelty of this work and highlight its unique contribution to the existing literature.

The remainder of this paper is organized as follows: Section 2 discusses the economics of PV modules in the current conditions of the Turkish Economy. Section 3 presents the methodology, introducing the data and economic applications. The results and discussion follow the methodology in Section 4. Finally, Section 5 provides conclusions and proposes some policy implications.

2. Economics of PV Modules in the Conditions of the Turkish Economy, as Well as in the World

2.1. Renewable Energy Targets: The Case of Solar Energy

In Türkiye, a large share of electricity is generated from fossil fuels (i.e., natural gas). However, some problems occur, such as a lack of domestic natural gas reserves, and population growth increases consumption, leading to a trade deficit for the country. On the other hand, Türkiye is expanding its interest in renewable energy in line with the global trend. Renewable energy's share in Türkiye's total electricity power reached around 52% in 2021, and the same statistic worldwide in the indicated period is around 38% [33]. To reduce the dependence on energy imports, the Turkish Government expressed its energy targets for 2023. Some of these targets that are related to our subject are also mentioned in [34–36]. This can be achieved by increasing the country's domestic energy potential. Some incentive mechanisms have been put in place to encourage investment in renewables. For example, licensing obligations, fees, and reduced permissions are provided. Besides, the government has guaranteed to buy electricity obtained from solar energy.

For Türkiye and the rest of the world, if total consumption of scarce and relevant materials for renewable energy systems grows, the PV module market will improve in terms of the availability of needed raw materials at suitable prices for manufacturing. These exciting challenges make the PV module industry economically more viable for future business scenarios [37].

2.2. Renewable Energy in Intended Nationally Determined Contributions (INDC) or Nationally Determined Contributions (NDC)

Renewable energy is a crucial factor in solving Türkiye's energy problems. This phenomenon can be summarized as Türkiye's heavy reliance on energy imports, finite fossil fuel reserves, high energy price inflation, environmental concerns, and challenges [38]. On the other hand, utilization of Türkiye's solar energy could reduce dependence on imported fossil fuels and help meet environmental commitments. On the other hand, the lack of financial support and regulatory instruments for developing solar energy systems has considerably delayed the utilization of the country's extensive solar potential [39].

2.3. Regulatory Policies

Various regulatory policies have been preferred to promote and encourage renewable energy. These instruments are fundamentally set out as laws governing pricing, production incentives, quota requirements, tax credits, and trading systems [40]. Specifically, the Turkish government's basic policy on solar energy is to support domestic solar panel production and to add 3000 MW of solar capacity by 2023 ([36,41]).

2.3.1. Feed-In Tariff (FiT)/Premium Payment

The FiT mechanism aims to lessen the cost of renewables. In other words, governments pay for renewable energy at a price above its market price through tariff applications [36,42]. Currently, FiT regulations for renewable energy (i.e., solar energy) exist in more than 40 countries worldwide, across both residential and commercial sectors [43,44]. The FiT mechanism is affected by many factors and depends on a country's technology level. For instance, countries with high levels of installed solar capacity could have lower incentives than those without. PV module producers are financially protected by applying fixed market prices through tariffs. They can adjust and forecast their cash flows over extended periods and make healthier decisions about their solar investments [45]. For instance, Italian markets have experienced a boom in PV module installations since the introduction of the first FiT in 2005 (see [46] for details). Concerning this, reference [47] proposed that it is very important to choose a suitable tariff scheme that opens the pathway of competitive markets and is necessary to avoid financial disturbances in this way. Another example is Germany, where a FiT system has proved successful, and, according to [48], this success can be applied elsewhere in the world. For instance, appropriate FiT mechanisms could achieve cost savings and improved cost-effectiveness, as shown in [49] for South Africa. As another example, reference [50] conducted an econometric analysis and found a positive correlation between the production of incentivized renewable energy and subsidies. Their estimates suggested that a 1% increase in FiT leads to an increase in PV module generation at around 0.4–1% in European countries (i.e., France, Germany, Italy, Spain, and the United Kingdom) from 2000 to 2010. Reference [51] presented an overview of the FiT policy's strength in the country and its necessity for Pakistan. Reference [52] showed that renewable energy (i.e., PV power systems) would not be economically feasible, even though a reasonable FiT mechanism exists in Algeria. This could be changed by increasing energy efficiency.

On the other hand, the FiT mechanism in Türkiye started in 2005 and is referred to as Phase I. However, it reached its final form with the 2010 Amendment Law, known as Phase II. It covers all renewable energy sources, including solar. Developing domestic manufacturing sectors and skills [8], and domestic equipment use is the priority for tariff supplements (one can reach Turkish government supplementary subsidies for PV systems in the price-energy unit ($/kWh) for differentiated sub-products in the studies of [34,39,53]. However, despite its effectiveness, the FiT mechanism could face some criticism, especially in one of the world's leading PV module markets (i.e., China). The main argument was that its implementation restricted the cost and innovation by removing incentives to reduce costs [54].

Feed-in Premiums (FiPs) are financial incentives that support renewable electricity production by providing a premium above the current market price. Unlike Feed-in Tariffs (FiTs), which guarantee a fixed price per unit of electricity, FiPs allow producers to sell electricity at market rates while receiving additional income for each unit generated. Therefore, it establishes both the sale of energy in the electrical market and the receipt of the premium, which are two sources of income for producers. The premium differs from FiT premiums based on the norms applied in each country (i.e., plant size, electricity generation costs, and technology type or energy source) [55].

2.3.2. Electric Utility Quota Obligation/Renewable Portfolio Standard (RPS)

A predetermined obligation imposed by the government regarding the use of a targeted minimum renewable energy share of installed capacity or of electricity generation provided by consumers or companies [56] is called an obligation. In addition, the RPS is likely the renewable obligation instrument. The government fixes the share of renewable energy produced in the energy portfolio in the indicated period. Compared to obligation, this instrument seems more efficient [57]; the energy policy triggers the rationale for the competition between PV module technologies. On the other hand, reference [58] noted that these instruments entail high negotiation and administrative costs [59].

2.3.3. Net Metering

Net metering is a billing method with fast growth of renewable energy investments for the last few years, such as residential PV module installations, primarily seen in the United States (for instance, reference [60] showed that net metering had significantly effect on PV module installations when the optimal amount was concerned by both monthly and annually for United States cities (Chicago, Phoenix and Seatle)) and Germany. This energy policy provides a cross-subsidy to distributed solar generation, paid for by all ratepayers [61]. In this method, electricity generated by PV modules in a residence is billed by a suitable meter. For example, as shown in Figure 1, if the total energy consumption at a residence is 100 kWh per month, and the energy produced and distributed to the grid is 30 kWh per month. The net bill at that residence would be 100 kWh − 30 kWh = 70 kWh × (electricity price/h). This example may change from region to region and period to period. However, governments are encouraging this environmentally friendly energy production method and offering promotions and incentives to reduce fossil fuel imports and CO_2 emissions. Figure 1 shows how net metering works through a PV module example: (1), solar panels convert energy from the sun into electricity (represented by number 2); (2), an inverter converts the electricity produced by the solar panels from direct current to alternating current for use in the house, school or business (represented by number 2); (3) The energy is used in the house, school or business (represented by number 3 and 4); (4) A bi-directional meter measures energy used and excess energy produced (represented by number 1).

This process not only promotes renewable energy usage but also provides financial incentives to reduce dependence on fossil fuels. Net metering contributes significantly to the growth of distributed solar energy worldwide, especially in regions with supportive policies.

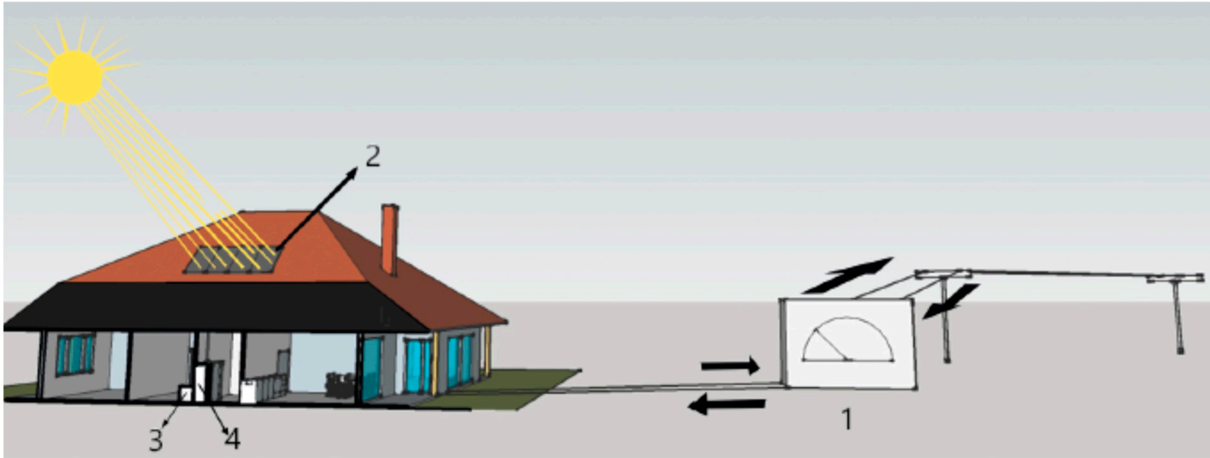

Figure 1. How net metering works (a PV module example). Note: This figure is initially drawn by the author using AutoCAD 2016 and SketchUp 8.

A theoretical economic model by [62] showed that, for residential use, the social welfare effects of both net-metering and FiT mechanisms, in the case of reduced electricity consumption, were either relatively small or relatively large. As an applied example, under the new Italian regulatory framework, reference [63] showed that, under net-metering conditions, a larger optimal PV plant size could be supplied, increasing PV energy surplus. As a result, the refund for the economic value of the electricity brought from the grid would increase. In this way, they found that the net-metering service served as an incentive scheme and a growth booster for the PV market in Italy. In their tariff-oriented microeconomic model, reference [64] showed that net-metering promoted greater environmental benefits and social welfare than other tariff schemes for residential PV modules.

It is important to mention that although net metering policies facilitate distributed solar PV adoption, their practical implementation depends on the technical acceptance and operational constraints of the local grid operator. Economic considerations or grid infrastructure restrictions may limit two-way electricity transmission. In periods of high solar irradiation and low household demand, reverse power flow from residential PV systems can exceed the distribution lines' hosting capacity, requiring curtailment or temporary disconnection for safety and stability. While such limitations are currently uncommon in Türkiye, they may become more pronounced over the 30-year operating horizon of PV systems as penetration increases. These factors highlight the importance of grid integration capacity when evaluating long-term economic feasibility under net-metering schemes.

2.3.4. Heat Obligation/Mandate

Consumers, producers, and generators of renewable energy, as parties, must set a minimum target and usually increase it over time. This is called a mandate or obligation. A percentage of supply, the amount of capacity, and the need for specific renewable technology can serve as examples of this issue. Mandates can sometimes include renewable portfolio standards (RPS), such as the obligation to deploy power technologies or to install renewable heat, with requirements for renewable heat purchases [56].

2.3.5. Tradable REC

Tradable REC is a renewable energy certificate that provides an instrument for trading and for accommodating renewable energy obligations among producers and consumers. It is crucial for voluntary green power purchases. Energy producers principally offer "green certificates" in kWh or MWh units. These certificates can be traded on the energy market and are added to the fundamental payment for electricity generated by renewable energy sources [65].

2.3.6. Tendering

Tendering is also called an auction or reverse auction. It's a mechanism for obtaining renewable energy capacity or supply through competitive bidding. Bids are offered at the lowest price and may be assessed based on non-price and price factors [56]. Regarding price measures, tenders are an indispensable part of support mechanisms for renewable energy electricity production. Governments and regulatory authorities are requesting bids for electrical energy supply in this system concerning a definite technology at a considerable (i.e., competitive) price. It is expected to develop the indicated technology. Once a fixed amount of capacity from renewable energy sources has been installed and connected to the electricity network, bidding among participants is conducted. The bids are determined as a fixed amount for a given location, technology, and capacity. The government establishes criteria for selecting a winning bid and aims to improve the location [55].

2.4. Fiscal Incentives and Public Financing

If contributions to the public treasury are reduced through income or taxes, the incentive applied to households (i.e., individuals) or companies is called a fiscal incentive. On the other hand, grants or loans, often provided by governments to support the deployment of solar energy technologies, are considered public financing [56].

This mechanism creates policies that primarily focus on advancing PV module competitiveness and reducing costs. The preferred reason for these instruments is the advantage of lower marginal costs of nonconventional systems compared to conventional ones (e.g., natural gas, hydro generation, thermal coal generation). Many countries (e.g., Türkiye) have therefore used these instruments, or combinations of them (i.e., both conventional and non-conventional), to facilitate their development [44], as discussed in our study.

2.4.1. Investment or Production Tax Credits

The expectation of future values or returns from the purchase of goods and services (e.g., manufacturing PV modules, researching PV module technology) is called an investment. On the other hand, when an inventor or property owner is subsidized by a tax incentive based on the amount of renewable energy generated (e.g., electricity produced by PV modules), it is called a production tax credit [56].

2.4.2. Reductions in Sales, Energy, CO_2, VAT, or Other Taxes

These instruments enable a reduction in the outgoing taxes, and this mechanism works through the profits earned from renewable energy projects. For instance, infrastructure projects can be exempt from income tax for a defined period [66].

2.4.3. Energy Production Payment

Energy production payments can be summarized as incentives for businesses, farmers, and homeowners to become producers of renewable energy or increase their production. According to [65], the energy production payment is defined as: "Direct payment of the government per unit of renewable energy produced".

2.4.4. Public Investment, Loans, Grants, Capital Subsidies, or Rebates

Public investment, loans, grants, and capital subsidies or rebates often rely on supporting mechanisms to finance PV module investments [67]. Specifically, an incentive exists to install hardware at inflated costs with capital subsidies [68,69]. These investments can take the form of government regulation or monetary assistance that reduces consumers' and producers' prices, or the initial investment in production costs for PV modules, which are sometimes not required to be repaid [56,66].

2.5. The Current Situation of the PV Modules Market in Türkiye and Eskisehir

Renewable energy was supported by various mixed technological developments and policies in most countries at the end of 2016, and the deployment continues. Türkiye is also affected by these global improvements and is working to implement the necessary policies, as shown in Table 1 below. These policies can be categorized by targeting economic development (i.e., falling costs or financial implications), national security (i.e., penetration of new technology or advancing domestic markets), and environmental protection (i.e., reducing CO_2 emissions or a clean environment) by supplying both direct and indirect supports [56]. Table 1 summarizes these support policies for Türkiye as an upper-middle-income country (i.e., the same table is available for the other countries in the Renewables 2017—Global Status Report in detail).

Table 1. Renewable Energy Support Policies for Türkiye.

	Regulatory Policies									Fiscal Incentives and Public Financing			
Country	Renewable energy targets	Renewable energy in INDC or NDC	Feed-in tariff/ premium payment	Electric utility quota obligation/RPS	Net metering	Transport obligation/mandate	Heat obligation/mandate	Tradable REC	Tendering	Investment or production tax credits	Reductions in sales, energy, CO_2, VAT, or other taxes	Energy production payment	Public investment, loans, or grants, capital subsidies or rebates
Türkiye	O	O	R			O			H				O

O—existing national (could also include sub-national)
R—Revised (one or more policies of this type)
H—Tenders held in 2016, as in past years

Source: [56]—Renewables 2017—Global Status Report.

The more the indicated energy support policies or regulations are implemented in Table 1, the more a country will become familiar with solar energy systems and be able to take a development path. Reference [70] argued that, in the province of Burkina Faso, PV module markets are not functioning as expected (i.e., continuously or sustainably) in the absence of promoting policies, programs, or regulations. To support this argument, reference [71] mentioned a dramatic decrease in Türkiye's self-sufficiency ratios in electricity usage, which was 77% in 1980 and dropped to 37% in 2014 and this tremendous change depended on high energy demand with increasing population, increased rate of fossil fuels (i.e., natural gas and hard coal), and insufficient utilization of renewable energy sources. Ozcan suggested using the energy policy as an instrument to address this decline and achieve energy independence. Table 1 shows that several policy instruments, such as direct investment subsidies, low-interest financing, or long-term tax exemptions, are either absent or only partially implemented for residential PV systems in Türkiye. Highlighting these gaps helps illustrate why additional policy support may be necessary to accelerate household solar energy adoption.

2.6. The Role of Local Governments and Their Effects on Cities

Sample countries and their government can examine the role of local governments and their effects on cities. For instance, local governments in China saw PV modules as an industrial opportunity in the last decade. This would pave the way for increased local employment and tax revenues in China [72]. A statistical study that includes models of US cities showed that strategic government interventions could be an effective policy instrument for promoting PV modules [73]. The economic viability of residential and commercial PV modules was analyzed for 314 districts of Chile in [74]. Their results showed that the feasibility of PV module installations increases as installation costs decrease, given the Chile's regulatory framework.

2.7. Technical Details and Financial Issues About PV Modules

To ensure terminological precision, the manuscript now consistently distinguishes among PV cells, PV modules, and the complete PV system. In this context, 'PV cells' refer to individual semiconductor units, 'PV modules' denote the assembled panels containing multiple cells, and 'PV system' refers to the full rooftop installation including modules, inverter, wiring, mounting hardware, and balance-of-system components.

Solar PV technology permits the direct conversion of sunlight into electricity through semiconductor devices called solar cells. Solar cells are interconnected and hermetically sealed to set up a PV module. PV modules are combined with other components, such as storage batteries, to form solar PV systems. PV systems are highly safe and interchangeable [75]. A PV system is made of cells, modules, inverters, etc. [28]. In this study, a PV module is referred to as a combination of those parts (as stated in the introduction). There are several options for installing PV modules; ground-mounted and rooftop systems are two widespread types [26].

In the global market, solar module improvements are driven by technological advances, with 90% of modules in 2014 using wafer-based crystalline silicon. PV module production was approximately 45 GWp in 2014; multi-crystalline-Si (mc-Si), mono-Si, and thin film accounted for 55%, 35%, and 9%, respectively. C-Si technology offers long-term durability and ample raw material availability; therefore, it has high solar cell efficiency [76]. In this study, the initial investment cost of a 3 kW residential PV system is taken as €7500, based on 2024 market prices.

The economic model is based on crystalline silicon PV panels, which account for approximately 90% of the Turkish and global residential PV market. In particular, multi-crystalline Si modules were assumed, with an efficiency range of 17–20%, consistent with the most commonly available PV modules in Türkiye's residential sector. Cost estimations—including installation, inverter replacement, and maintenance—were derived using this technology type as the reference case.

Based on data from the Turkish State Meteorological Service and PVGIS (Photovoltaic Geographical Information System), Eskisehir receives approximately 1550–1600 kWh/m^2/year of Global Horizontal Irradiation (GHI). Under these conditions, a typical 3 kW south-facing, optimally tilted crystalline silicon PV system in Eskisehir generates: 3900–4300 kWh/year of electricity (capacity factor $\approx$ 15%). This value is fully aligned with national PV yield data. It confirms that Eskisehir performs close to the Turkish national average and significantly higher than northern European countries (e.g., Norway $\approx$ 900–1100 kWh/kW/year).

3. Methodology: A Life-Cycle Cost Analysis with the Survey and Institutional Data

3.1. The Obtained Data from the Survey, Various Sources, Restrictions, and Assumptions for the Variables

Our data was obtained from a 2013 survey conducted in Eskisehir, Türkiye. The questions were randomly distributed to residents of Eskisehir. We began by identifying the total number of households and computing the average number of nuclear families in our sample, which provided an overall profile of the survey. We also considered climatic factors that could affect household energy consumption.

Both open-ended and multiple-choice questions were included in the survey, and 154 respondents were invited to answer the questionnaire. The respondents had different incomes and had several other occupations (i.e., academic staff, engineers, employees, officers, and teachers). We used this data to help support our theoretical findings. In other words, our study could have been conducted without this self-administered survey; however, we believe it added originality to our work. One can find detailed information about the survey, including tables and statistics (e.g., Table 6a,b in [77]).

We designed the survey for multiple purposes since we had various hypotheses about solar energy systems. However, this study primarily focused on a household's energy consumption. The total energy consumption of each household was measured and summed because household energy demand was directly related to electricity consumption, and PV modules generated that electricity. Additionally, respondents were asked about their type of residence and the electrical appliances they owned. Beyond electricity usage, data on energy consumption for cooling, heating, and lighting were collected through related questions.

In earlier versions of this study, a 2013 household survey was referenced to provide contextual insight into historical perceptions of solar technologies in Eskisehir. However, this survey is no longer used as a primary empirical input in the economic model. Instead, the analysis has been updated to rely on recent national and regional datasets (2021–2023), including household electricity consumption statistics from TÜİK, current PV installation cost reports from EPC providers, and contemporary market data. These updates ensure that the parameters used in the life-cycle cost analysis reflect present-day conditions. The 2013 survey is now cited only as background information rather than as representative data for 2024.

All variables included in the life-cycle cost analysis operate under explicitly defined constraints. Inflation and discount rates are assumed to remain stable within the 9–10% range, in line with CBRT's long-term macroeconomic projections. Fuel price inflation is restricted to the 9% baseline scenario unless otherwise stated. PV system lifetime is fixed at 30 years, with replacement costs allocated after year 15. Property taxes, maintenance, and parasitic energy costs are assumed to increase at a controlled rate of 7%. These restrictions reflect realistic boundary conditions for the Turkish economy and ensure analytical consistency across all presented scenarios.

3.2. Methods: Time Versus Money Dimension

The most effective way to connect consumers with technologically advanced, environmentally friendly PV modules is to address the nation's energy needs using its domestic resources. Figure 2 demonstrates the concept of this study through consumers and producers. The fundamental issue with consumers buying these devices and feeling safe is that the utility of their payments should outweigh all the included costs. This can be solved by each consumer who knows their investment payback period. According to this study, the consumer will have a 30-year investment plan for these devices, which includes financial and cost conditions, with constraints on inflation and interest rates in the Turkish Economy, along with net present value calculations. The value-added tax issues are also included in these calculations. To ensure the widespread adoption of these domestically manufactured devices, consumer demand is strongly dependent on maintaining stable inflation and interest rates and providing government-controlled tax incentives. These controlled market dynamics are a crucial event for the Turkish Government.

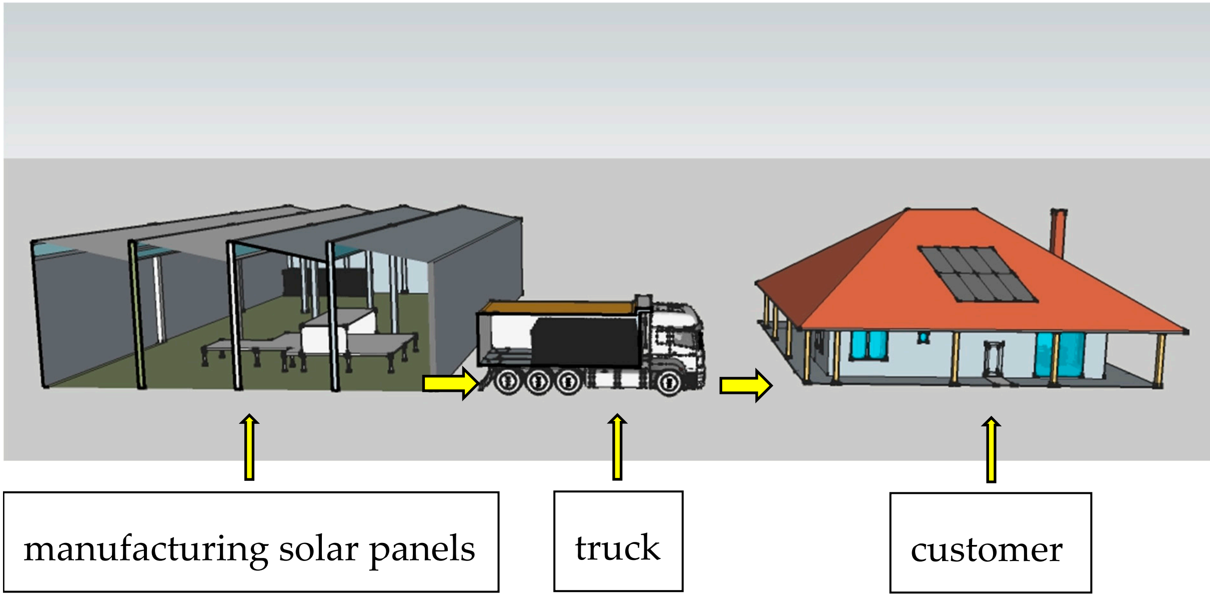

Figure 2. Schematic diagram illustrating the concept of this study. Solar modules are produced in factories, loaded onto trucks, and shipped to customers. Note: This figure is initially drawn by the author using AutoCAD 2016 and SketchUp 8.

Figure 2 outlines the core relationship between consumers, producers, and government incentives in the adoption of PV systems. It highlights the role of financial planning, tax benefits, and stable market dynamics in fostering renewable energy adoption, emphasizing a 30-year investment horizon.

Building on this concept with more technical terminology, this study employs life-cycle cost analysis for economic evaluation. This method focuses on the time value of money while accounting for various cost categories. Our analysis follows [21,78,79] by adapting the mentioned arguments to the Turkish economy. In the following subsections, some pricing methods will be explained and given with practical life examples.

3.2.1. Cost of PV Modules

The primary challenge in manufacturing solar PV modules is determining the optimal panel size that minimizes energy costs. However, this size is typically selected at random from a local free-market firm in Türkiye. Additionally, the purchase and installation of a residential grid-connected PV system involves investment components such as PV modules, mounting structures, inverters, wiring, protection devices, and the grid connection interface. In addition to the equipment purchase price, installation costs should be considered. The installation costs of a PV module can be seen in Equation (1) as:

$$C_p = C_a \times A_p + C_e \tag{1}$$

where

C_p: Total cost of installed PV equipment (€)

C_a: Total area-dependent costs (€/m^2)
A_p: Panel area (m^2)
C_e: Total cost of PV equipment, which is independent of panel area (€).

Here, C_a includes purchasing and installing the module, as well as storage costs. In the context of a PV system, C_e represents the installation-related expenses that depend on the installed capacity. This includes the cost of PV modules and mounting structures, which scale directly with the panel area, as well as wiring, protection devices, and DC/AC inverters, which scale indirectly with system power output (kW), and are therefore also influenced by the deployed PV area.

In a general form, that explains both non-solar and solar energy systems in one equation can be shown with Equation (2) which provides the detailed formulation of the module-related cost term that appears in the installation cost expression of Equation (1). Thus, Equation (2) should be interpreted as a component-level breakdown that feeds directly into C_e in Equation (1), linking the panel area and unit cost assumptions to the total installation cost of the PV system.

$$Y_c = F_e + M_p + M_i + PEC + PT - ITS \tag{2}$$

where

Y_c: Yearly cost
F_e: Fuel expense
M_p: Mortgage payment
M_i: Maintenance and insurance
PEC: Parasitic energy costs
PT: Property taxes
ITS: Income tax savings.

Here, F_e represents the conventional system. M_P denotes the payment required to install the PV cell system, including both interest and principal payments on any loans used to purchase solar energy equipment. M_i refers to the costs necessary to maintain the system in good working condition. PEC refers to the auxiliary energy consumed by system components, such as inverters and cooling mechanisms, during operation. PT is the tax imposed on installations. ITS is categorized into two systems. The first category pertains to non-income-producing systems and can be expressed in Equation (3) as:

$$ITS = ETR \times IP + PT \tag{3}$$

Here, ETR represents the effective tax rate, and IP denotes the interest payment.

The second category refers to income-generating installations, such as systems producing electricity for sale to the grid, and can be expressed in Equation (4) as:

$$ITS = ETR \times (IP + PT + F_e + M_i + PEC - \text{depreciation}) \tag{4}$$

The Effective Tax Rate (ETR), calculated using Equation (5), accounts for both federal and local taxation, adjusted to reflect value-added tax (VAT) in the Turkish context:

$$ETR = FTR + STR - FTR \times STR \tag{5}$$

While FTR stands for the federal tax rate, STR represents the state tax rate (i.e., Türkiye has not contained any states; she has only contained cities, and Eskisehir is one of them. So, in our analysis, the federal or state tax is changed with "value-added tax" (VAT).

The concept of solar savings is well argued by [21,80]. This concept can be given in Equation (6) as:

$$\text{Solar savings} = \text{Costs of conventional energy} - \text{costs of solar energy} \tag{6}$$

Solar savings are defined as the difference between the costs incurred using conventional energy systems and the reduced costs achieved through solar energy systems.

One can express Equation (6) in common terms for both conventional and non-conventional systems, as it is stated in Equation (7):

$$\begin{gathered}\text{Solar savings} = \text{fuel savings} + \text{income tax savings} - \text{incremental property tax} - \text{incremental} \\ \text{mortgage payment} - \text{incremental parasitic energy cost} - \text{incremental insurance and maintenance}\end{gathered} \tag{7}$$

Equations (6) and (7) are different expressions for solar savings. Since energy is the purpose and savings are the vehicle for consuming energy effectively, the transformation from Equation (6) to Equation (7) helps readers express solar savings as net savings, equal to positive savings minus the energy system's costs.

Now, it is time to make analogies between Equations (3) and (4), and between Equations (8) and (9) to express ITS for both non-income-producing and income-producing solar energy systems.

$$\text{ITS} = \text{ETR} \times (\text{incremental interest payment} + \text{incremental property tax}) \tag{8}$$

$$\begin{gathered}\text{ITS} = \text{ETR} + (\text{incremental parasitic energy cost} + \text{incremental property tax} + \text{incremental maintenance and} \\ \text{insurance} + \text{incremental depreciation} + \text{incremental interest payment} - \text{the value of fuel saved})\end{gathered} \tag{9}$$

3.2.2. Design for the Lowest Cost

The primary objective in designing solar energy systems is to minimize the overall cost. System efficiency is closely related to the PV module's area. Given a load with storage capacity, the other variable for the system is the module area. Economic analyses strongly depend on the module area and the system's performance.

3.3. Economic Approaches for Optimal Design

There are many economic approaches for implementing the optimal designs for solar energy systems. Each system has its advantages, but there is no strict consensus on which is most suitable. Let's define the most popular ones.

3.3.1. Least Cost Solar Energy

Minimizing operational costs over the system's lifecycle is called the least-cost solar energy approach. This method considers only solar energy; in other words, it does not account for conventional energy sources.

3.3.2. Life-Cycle Cost (LCC)

Once an energy system is installed, the energy provided over its operational lifespan during a specified analysis period is referred to as LCC. This concept encompasses costs and accounts for the time value of money. The principle involves applying a market discount rate (reflecting the rate of return on the best alternative investment) to convert future costs to present value and determine the required investment amount. In addition, this method can estimate future expenses by incorporating current economic inflation rates.

3.3.3. Life-Cycle Savings (LCS) (Net Present Worth)

LCS represent the net financial benefit of using a solar-plus-conventional system compared to a conventional fuel-only system. It is calculated as the difference between the

Life-Cycle Cost (LCC) of the two systems. LCS depends on the cash flow (net payments) of the right-hand side variables in Equation (2).

3.3.4. Annualized Life-Cycle Cost (ALCC)

ALCC stands for the average annual cash flow. The same procedure can be applied to annualized life-cycle savings (ALCS).

3.3.5. Payback Time

There are various definitions of payback time, but the most common is the time required for the equity of the total initial investment to equal the total fuel savings. The Energy Payback Time (EPBT) of PV systems, which measures the time required to recover the energy invested in their production through energy generation, was calculated to range from 8 to 16 years in a cost analysis conducted in India [81]. Figure 3 shows this phenomenon. In Figure 3, while the abscissa includes time (years), the ordinate consists of cash flow (€). Points A, B, C, D, and E refer to the time needed for a positive cash flow, for getting an investment back by saving fuel, for the cumulative savings to end up with zero, for the cumulative savings to be the same as with the down payment for the solar energy system, for the cumulative savings to be same as with the remaining debt principal on the solar energy system, respectively. According to this Figure, the most general definition of payback time corresponds to point B.

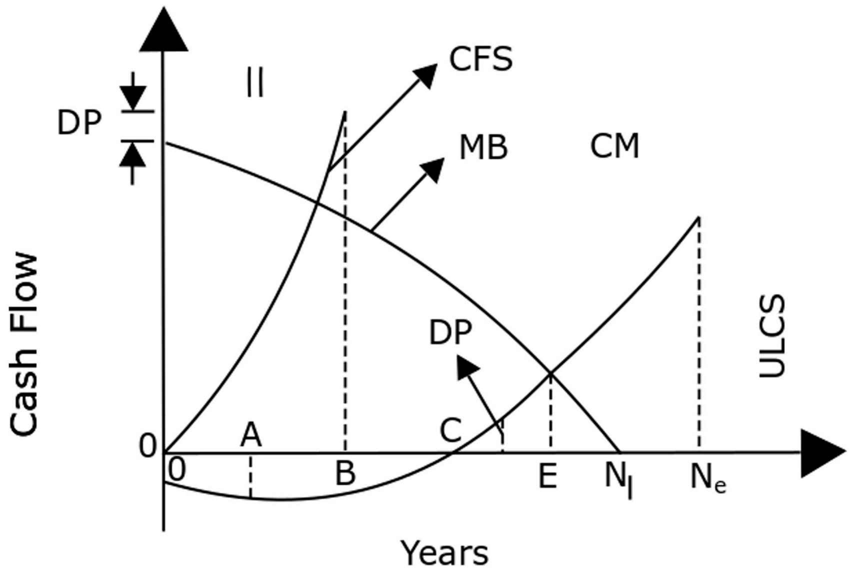

Figure 3. Changes in mortgage balance, cumulative savings, and cumulative fuel savings, as a function of time. Note: This figure was originally adapted from [21] using AutoCAD 2016.

This figure demonstrates the financial impact of PV system investments over time, illustrating milestones such as achieving positive cash flow, recovering investment costs, and breaking even with cumulative savings.

3.3.6. Return on Investment (ROI)

The ROI is the given discount rate, which makes the present worth's of solar and non-solar alternatives equal, as shown in Figure 4 below. In Figure 4, while the apsis includes discount rates, the ordinate includes LCS. This Figure shows an example of life-cycle savings as a function of the market discount rate.

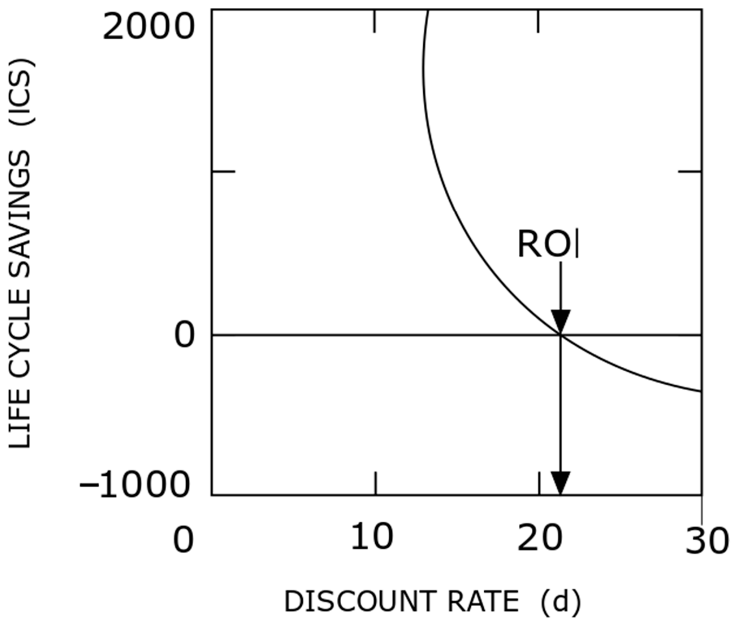

Figure 4. An example of life-cycle savings as a function of market discount rate. Note: This figure was originally adapted from [21] using AutoCAD 2016.

This figure highlights the relationship between market discount rates and the net present value (NPV) of savings, offering insights into the financial feasibility of PV systems under varying economic conditions.

3.4. Discounting Factors and Inflation Rates

The life-cycle method considers future expenses with today's costs. The present worth of future expenses is calculated based on predictions of a country's economic conditions, such as inflation rates and discount rates. The most effective alternative can be determined by calculating the present values of all future costs for both solar and non-solar cases, yielding the lowest life-cycle cost. Time plays a vital role in relation to the value of money and the rational decisions consumers make. Therefore, the investment's cash flow must be discounted to a reliable amount. The relationship between "present worth" of 1€ and a given market discount rate "d" for the indicated life span of N (years) is calculated by Equation (10), seen below as:

$$\mathrm{PW} = 1/(1 + \mathrm{d})^{\mathrm{N}} \tag{10}$$

Since we consider a particular lifetime, we can assume that in each period, costs would inflate or negatively inflate (deflate) at a fixed percentage. This relationship is shown in Equation (11) as follows:

$$\mathrm{C_N} = \mathrm{A} \times (1 + \mathrm{i})^{\mathrm{N}-1} \tag{11}$$

where C_N is the cost value at the Nth period, A is the initial payment or cost, and i is the inflation rate (if negative, it is the deflation rate).

Given an interest rate i, one can understand the idea behind total payments during the N period or lifetime of the investment and the present worth of the total payments in Figure 5 as follows:

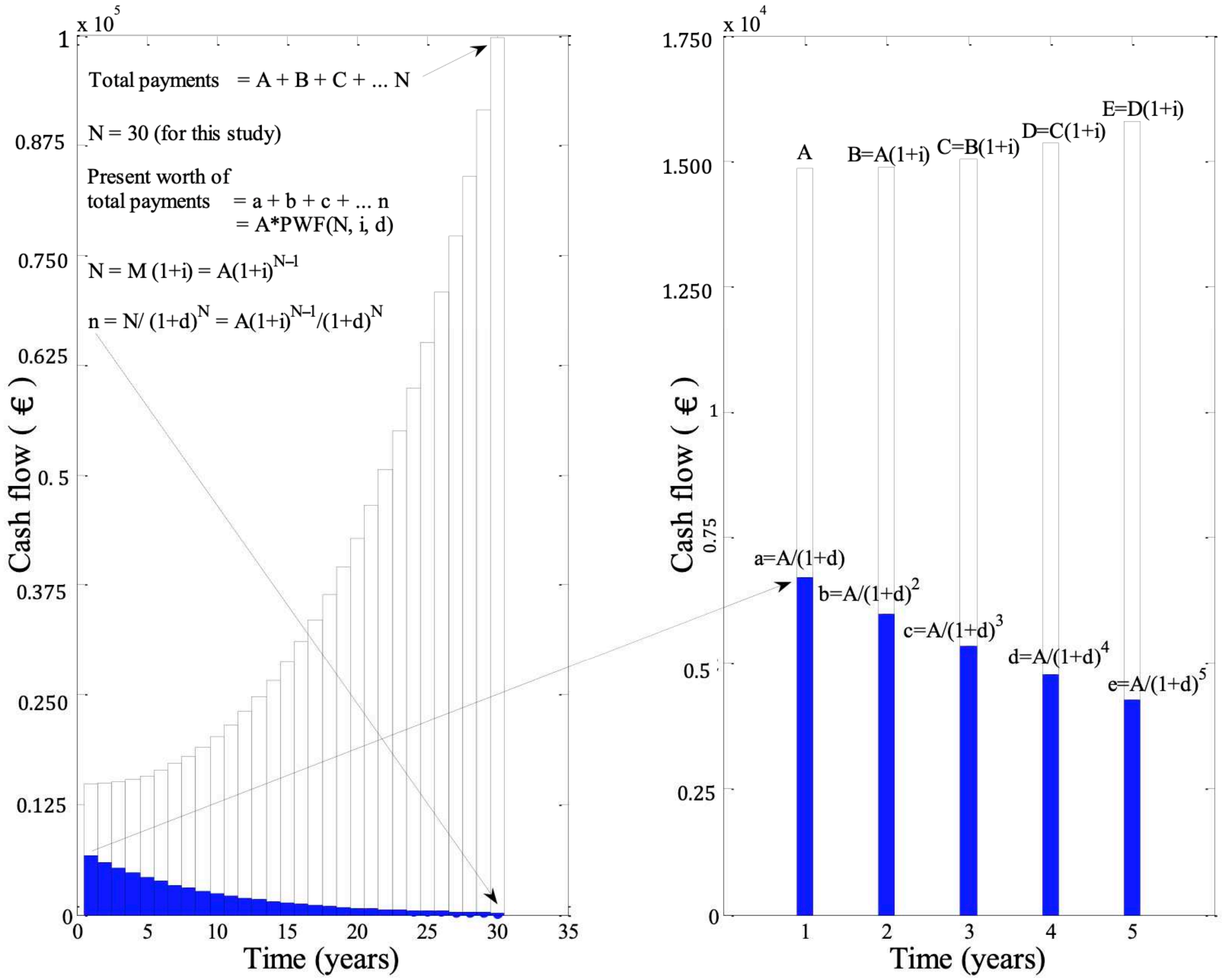

Figure 5. Time-money phenomenon of total payments for the lifetime of a PV module investment in the Turkish Economy. Note: This figure is drawn by the authors based on Equations (12) and (13). The MATLAB R2019b code for producers, consumers, and the government for any year's lifetime can be provided upon request.

Figure 5 visualizes the cash flow associated with PV module investments, comparing the present value of payments over the investment lifetime. The representation underscores the importance of time value in financial decision-making.

As illustrated in Figure 5, the shaded portions of the bars represent the present value of the anticipated payments. In contrast, the full height of the bars reflects the total payments over the investment's lifetime. Besides, at the end of the lifetime, the cost is $A \times (1 + i)^{N-1}$, and the present worth of the Nth payment is calculated from Equation (12) as follows:

$$PW_N = (A \times (1 + i)^{N-1})/(1 + d)^N \tag{12}$$

Figure 5 assumes that the payments are made at the end of each period. Of course, there is another possibility: payments are made at the beginning of each period. In this case, Equation (11) can be described as: $C_N = A' \times (1 + i)$ and Equation (12) can be expressed as: $PW_N = A' \times ((1 + i)/(1 + d)^N)$.

3.5. The Definition and Use of "Present-Worth Factor"

We need a general mathematical function that determines the Nth present-worth factor (PWF). The formula can be seen in Equation (13) with a given inflation rate i and discount rate d below:

$$\text{PWF(N, i, d)} = \sum_{J=1}^{N} \frac{(i+i)^{j-1}}{(1+d)^{j}} = \begin{cases} \frac{1}{d-i}\left[1-\left(\frac{1+i}{1+d}\right)^{N}\right] & if\ i \neq d \\ \frac{N}{1+i} & if\ i = d \end{cases} \quad (13)$$

With some mathematical manipulation, PWF can be used to determine the periodic payment for the loan. It is assumed that all mortgage payments remain unchanged under a stable inflation rate of "0". Along with these assumptions, "*d*" in Equation (13) becomes a mortgage interest rate, and the Periodic payment of a loan for N periods is then calculated from Equation (14) as follows:

$$\text{PP}_{\text{L}} = \frac{M}{PWF\ (N_L,\ 0,\ m)} \quad (14)$$

where M is the mortgage principal, N_L is the mortgage period, and m is the mortgage interest rate.

The total present worth of all the mortgage payments can be calculated much more easily with the following formula. Equation (15) includes the PWF for this calculation as follows:

$$\text{PW}_{\text{int}} = \text{M} \times [\frac{PWF\ (N_{min},\ 0,\ d)}{PWF\ (N_L,\ 0,\ m)} + PWF\ (N_{min},\ m,\ d)\ (\text{m} - \frac{1}{PWF\ (N_L,\ 0,\ m)})] \quad (15)$$

where M is the initial mortgage principle, N_L is the mortgage term, N_e is the term for economic analysis, N_{min} is the lesser of N_L or N_e, and m is the mortgage interest rate.

3.6. Life-Cycle Savings Method for Practical Applications

The ideas obtained by discounting future costs will now be used and applied through our concept in various examples. One can also define these examples as scenarios for Eskisehir. Besides, the costs used can vary from location to location due to economic conditions, government legislation, and global developments closely related to energy prices.

4. Results and Discussion

4.1. Results

We start with a basic example of an installed solar system and gradually improve our analysis by adding details. It is anticipated that the PV module system will require replacement after years (i.e., the replacement period for these solar energy systems has been extended from 10 to 15 years in recent times). Because the quality of the used materials and their technology has been highly improved. For instance, new materials are generated between glass and metal for insulation which have very long durable capacity and sensitiveness to both hot and cold.), with a replacement cost of €250 (i.e., the life time of the system is 30 years and the total price is €7500 (see Appendix A Note 1). So, at the end of 1 year the cost would be €250) at that time. Given a 9% inflation rate and a 10% discount rate [77], let's calculate the present worth of replacing the PV module system using Equation (12) (see Appendix A Note 2). Therefore, under the specified economic conditions, the present value of replacing the PV module system after 15 years (PW15) is calculated as €200.

As a second step, we need to calculate the present value of a series of 30 annual payments (cumulative over the lifetime of the energy system), starting with €250. These payments are expected to increase by 9% per year due to inflation, while the market discount rate remains 10% per year, consistent with the previous calculation (Equation (13)). From Equation (13), the present worth of the 30-year series is €5991.25 (see Appendix A Note 3).

As a third step, we first need to calculate the yearly periodic payment and yearly interest charge for a €7500 PV module installation, financed with a 15% down payment and the remaining balance borrowed at an annual interest rate of 10% for 30 years. Payments will be made at the end of each year, with a market discount rate of 10%. Then, let's calculate the present worth of the series of interest payments (Table 2).

Table 2. Progression of payments, remaining principal, interest payment, and present worth of the interest payment (€).

Year	Mortgage Payment	Remaining Principle	Interest Payment	Present Worth of Interest Payment
1	678	6334	638	580
2	678	6290	634	524
3	678	6240	629	473
4	678	6186	624	426
5	678	6127	619	384
6	678	6061	613	346
7	678	5989	606	311
8	678	5910	599	280
9	678	5823	591	251
10	678	5727	582	225
11	678	5621	573	201
12	678	5505	562	179
13	678	5377	551	160
14	678	5237	538	142
15	678	5082	524	125
16	678	4912	508	111
17	678	4725	491	97
18	678	4520	473	85
19	678	4293	452	74
20	678	4045	429	64
21	678	3771	405	55
22	678	3470	377	46
23	678	3138	347	39
24	678	2774	314	32
25	678	2373	278	26
26	678	1932	237	20
27	678	1447	193	15
28	678	914	145	10
29	678	327	92	6
30	678	−319	33	2
The worth of the interest payments				5283.25

Note: This table is generated by applying the equations in the theoretical framework to Türkiye's financial inputs. Therefore, the unit of economic values is €. However, one can be curious about a specific country or a region. In that case, the algorithm for the designed table can be provided upon request, provided the initial solar investment payment and the location's financial structure are specified.

For the calculation of the annual periodic payment, we can use Equation (14). The mortgage or the present worth of the sum of all payments is equal to (i.e., $0.85 \times$ €7500 = €6375) €6375. The yearly periodic payment is then calculated at €678.25 (see Appendix A Notes 4 and 5).

An alternative solution for the total present worth of all mortgage interest payments can be calculated using Equation (15) in Appendix A Note 6.

4.2. Application of Life-Cycle Saving Methods in Eskisehir's Economy

In this part of the study, we provide examples intended to illustrate the method of life-cycle saving. The various costs used in these examples refer to Eskisehir's economy. However, these costs tend to vary widely from location to location, depending on the time-money dimension and related government legislation. The prices would vary depending on the prevailing market conditions.

First, we start with a non-solar energy system, with a given financial scenario, and try to calculate the present worth of the fuel cost for a non-solar energy system using fuel only, over 30 years if the first year's cost is (i.e., (€33.5 + €5.5) × 12 years = €39 × 12 years = €468) €468 [82]. The market discount rate is 10% per year, and the fuel cost inflation rate is 9% per year. The current fuel cost value in column 2 of Table 3 is obtained by multiplying each previous year's fuel cost by (1 + i), and each row of the present worth of fuel cost is calculated by using Equation (10) or multiplying the first year's fuel cost by PWF(30, 0.9, 0.1). Under the baseline scenario, a conventional energy system reliant on natural gas, the total fuel expenditure is projected to be €11,215.50 over 30 years, based on Eskisehir's economic conditions.

Table 3. Progression of fuel cost, present worth of fuel cost, and the cumulative worth of the fuel cost (€).

Year	Fuel (Natural Gas) Cost	Present Worth of Fuel (Natural Gas) Cost
1	468	426
2	510	422
3	556	418
4	606	414
5	661	410
6	720	407
7	785	403
8	856	399
9	933	396
10	1017	392
11	1108	388
12	1208	385
13	1316	381
14	1435	378
15	1564	375
16	1705	371
17	1858	368
18	2025	364
19	2208	361
20	2406	358
21	2623	355
22	2859	351
23	3116	348
24	3397	345
25	3703	342
26	4036	339
27	4399	336
28	4795	333
29	5226	330
30	5697	327
The worth of fuel (natural gas) cost		11,215.5

Note: This table is designed by applying the equations given in the theoretical framework to the financial inputs for Eskisehir. Therefore, the unit of economic values is €. However, one can be curious about a specific city or a region. In that case, the algorithm for the designed table can be provided upon request, provided the initial solar investment payment and the location's financial structure are specified.

Now we illustrate a similar scenario, but in this case, fuel costs are expected to rise at rates that depend on the country's economy over the life-cycle of a non-solar energy system. The basic idea here is the fluctuation in energy cost. A stable economy can enable more efficient market transactions, and this can be achieved through a strong government that pays close attention to energy policy. If we want to calculate the present worth of fuel cost for a non-solar energy system, using fuel only, over 15 years, if the first year's cost is €468, it inflates at 8% per year for five years, and then it inflates at 5% per year, with a market discount rate of 7% per year. Table 4 shows the fuel cost and present worth of the fuel cost using Equation (10). With varying inflation rates, the sum of expected payments is 77% greater than the present worth of the payments. As someone can easily notice in the condition of $i > d$, the present worth increases, and the opposite happens when $i < d$.

Table 4. Progression of fuel cost, present cost of fuel, and the cumulative cost of the fuel with a changing inflation rate (€).

Year	Fuel (Natural Gas) Cost	Present Worth of Fuel (Natural Gas) Cost
1	468	438
2	506	442
3	546	446
4	590	450
5	637	454
6	688	458
7	722	450
8	758	441
9	796	433
10	836	425
11	878	417
12	922	409
13	968	402
14	1016	394
15	1067	387
Total	11,394.75	6443.5

Note: This table is designed by applying the equations given in the theoretical framework to the financial inputs for Eskisehir. Therefore, the unit of economic values is €. However, one can be curious about a specific city or a region. In that case, the algorithm for the designed table can be provided upon request, specifying the initial payment for the solar investment and the financial structure (varying inflation rates and a constant discount rate) for the location.

4.3. A Critical Discussion: Combination of Solar and Conventional Energy Systems by Considering Future Savings or Costs in the Financial Conditions in the City of Eskisehir

The same methods are now applied to assess combined solar and conventional energy systems, accounting for future savings and associated costs. As mentioned in the concept of our study, a combined solar and fuel system to meet the previously mentioned energy needs is to be considered. The suggested PV modules and related equipment are projected to reduce fuel consumption by 60%, for €7500. This system will be financed at 90% over a 30-year term with an interest rate of 10% [77]. For a system lacking solar components, the fuel cost in the first year would amount to €468, with an anticipated annual increase of 9% [77]. It is projected that the equipment will retain 40% (i.e., €7500 × 0.4 = €3000) of its initial value at the end of the 30 years (i.e., €7500 × 0.4 = €3000). Additional costs in the first year, including insurance, maintenance, and parasitic energy, are estimated at €1000, with extra property taxes amounting to €1250 (i.e., €7500 × 18% VAT = €1350 ≈ €1250). These costs are expected to rise at an inflation rate of 7% annually (note that when these calculations were made, the general inflation rate was 9%; however, it is expected to decrease with political stability). Notably, extra property taxes and mortgage interest are excluded from taxable income; thus, the effective income tax rate is expected to be around 45% [83] throughout the life-cycle analysis. Therefore, our critical question is: What is the present value of the solar savings over 30 years, assuming a 10% discount rate?

Table 5 shows the incremental yearly savings and costs. Year 1 includes estimates of the first year's cost, and the detailed information and calculation steps for years 1 and 2 are provided below. The annual payment on the €6750 mortgage (i.e., €7500 × 0.9 = €6750) is calculated (i.e., €6750/PWF(30,0,0.10) = €715.75) as €715.75. The steps in the tax savings are outlined in Equation (3) (see Appendix A Note 7). Solar savings are obtained by summing each year's columns from column 2 to column 6. Each year's solar savings is calculated by using a market discount rate of 10%. The down payment is €750, and it is entered in the table in year "0" in columns 7 and 8, which show the equality between solar savings and the present worth of solar savings, but with a negative sign. The resale value is also included in Table 5 and appears as a second entry the following year, "30", with a value of €3000 (i.e., €7500 × 0.4 = €3000), which contributes to savings at the end of 30 years. With the inclusion of resale value, the sum of the last column is €883.75. This value corresponds to the total present worth of the gains from the solar energy system compared to the fuel-only system. The life-cycle solar savings of the PV module for 30 years in Eskisehir, and this finding is validated by the International Renewable Energy Agency (IRENA), in 2024 [84]. IRENA reports that the global capacity-weighted average total installed cost of PV projects commissioned in 2023 was around €720/kW (i.e., $758/kW), 86% lower than in 2010 and 17% lower than in 2022. It should be underlined that this value is around 23% lower than our finding.

Table 5. Solar savings from a PV module in Eskisehir in a 30-year lifetime period (€).

Years	Fuel Savings	Extra Mortgage Payment	Extra Insurance Maintenance Energy	Extra Property Tax	Income Tax Savings	Solar Savings	Present Worth of Solar Savings
0	-	-	-	-	-	−750	−750
1	281	−716	−33	−42	323	−188	−171
2	306	−716	−36	−45	322	−168	−139
3	334	−716	−38	−48	322	−147	−110
4	364	−716	−41	−51	321	−123	−84
5	396	−716	−44	−55	320	−98	−61
6	432	−716	−47	−59	319	−70	−40
7	471	−716	−50	−63	318	−40	−20
8	513	−716	−54	−67	317	−6	−3
9	560	−716	−57	−72	315	30	13
10	610	−716	−61	−77	314	70	27
11	665	−716	−66	−82	312	113	40
12	725	−716	−70	−88	309	160	51
13	790	−716	−75	−94	307	212	62
14	861	−716	−80	−101	304	269	71
15	938	−716	−86	−108	301	330	79
16	1023	−716	−92	−115	297	398	87
17	1115	−716	−98	−123	293	471	93
18	1215	−716	−105	−132	289	551	99
19	1325	−716	−113	−141	284	639	105
20	1444	−716	−120	−151	278	735	109
21	1574	−716	−129	−162	272	839	114
22	1715	−716	−138	−173	264	953	117
23	1870	−716	−147	−185	256	1078	120
24	2038	−716	−158	−198	247	1214	123
25	2222	−716	−169	−212	237	1362	126
26	2421	−716	−181	−227	225	1524	128
27	2639	−716	−193	−243	213	1701	130
28	2877	−716	−207	−260	199	1894	131
29	3136	−716	−221	−278	183	2104	133
30	3418	−716	−237	−297	165	2334	134
30						3000	172
Total present worth of solar savings =							883.75

Note: This table is designed by applying the equations given in the theoretical framework to the financial inputs for Eskisehir. Therefore, the unit of economic values is €. However, one can be curious about a specific city or a region. In that case, the algorithm for the designed table can be provided upon request, provided the initial solar investment payment and the financial structure of the location (predicted inflation rates and a constant discount rate) are specified.

PV module technology is developing fast. In line with this development, the role of low-cost PV systems in addressing the world's environmental and energy-related crises is likely to be crucial [85]. On the other hand, the use of PV modules is insufficient compared to Türkiye's potential. The reasons behind this fact are closely related to a low level of consciousness and awareness of renewable energy resources and their applications in society [36,86]. In addition, selecting the appropriate incentive type given the country's current condition is crucial. Decision-makers in governments should be informed about the proper incentive scheme, as is done in this research!

4.4. Evaluation of Results for Different Scenarios

To address long-term uncertainty over the 30-year operational period of the PV system, a scenario analysis was conducted based on three alternative policy and economic trajectories: (i) a worst-case scenario assuming the removal of all subsidies and reduced net-metering benefits, (ii) a business-as-usual scenario reflecting current policy and economic conditions, and (iii) an optimistic scenario incorporating stronger environmental regulations such as potential CO_2-pricing and future declines in PV technology costs. These scenarios, which are presented in Table 6, enable a more comprehensive assessment of the robustness of the life-cycle cost and NPV outcomes under plausible future developments.

Table 6. Scenario analysis results table.

Scenario	Key Assumptions (Summary)	Scaling Factor	Present Worth of PV Benefits	Change in Initial Investment Cost	Estimated NPV (Approx.)
Worst-case	−10% annual PV yield; net-metering benefits reduced by 50%; −10% present-worth effect; +10% installation cost	0.405	€357.92	+€750	€−392.08
Business-as-Usual (BAU)	Baseline policy and economic assumptions (original model)	1.00	€883.75	€0	€883.75
Optimistic	+10% PV yield; +20% policy/environmental incentive effect; +5% discount-rate effect; −15% installation cost	1.386	€1224.88	−€1125	€2349.88

Note: Scenario values are computed by the authors based on the assumptions detailed in Section 4.4.

The scenario analysis highlights how strongly the long-term economic performance of a 3 kW residential PV system depends on policy conditions, market stability, and technological progress. Under the worst-case scenario, where incentives are removed, net-metering benefits are significantly reduced, and installation costs increase, the system yields a negative NPV (−€392), demonstrating that unfavorable regulatory or economic developments can render the investment uneconomical over a 30-year horizon. The business-as-usual scenario, which reflects current market and policy conditions, aligns with the study's original findings and yields a moderately positive NPV (€884), indicating that PV adoption is economically feasible under current circumstances. In contrast, the optimistic scenario, which assumes improved environmental policies, more substantial financial incentives, and further declines in PV technology costs, produces a substantially higher NPV (€2350), underscoring the potential economic benefits that supportive policy interventions can unlock. Overall, the results demonstrate that residential PV investments are susceptible to future policy and economic trajectories, and they highlight the value of scenario-based evaluation for long-term decision-making.

Furthermore, the environmental benefits of the PV system were quantified by calculating the avoided CO_2 emissions associated with displaced grid electricity. Annual avoided emissions were computed as in Equation (16):

$$CO_2\text{,avoided} = \text{EPV} \times \text{EFgrid} \quad (16)$$

where EPV is the annual electricity generated by the PV system (adjusted for degradation), and EFgrid is the Turkish grid emission factor. Based on recent IEA and national reports, an emission factor of 0.358 kg CO_2/kWh was used. Under the business-as-usual scenario, the PV system avoids approximately 1.47 tons of CO_2 per year, resulting in a cumulative avoidance of 44.1 tons of CO_2 over 30 years. These results demonstrate that, beyond economic viability, residential PV adoption in Eskisehir provides meaningful environmental co-benefits through reduced reliance on fossil-based grid electricity.

In this study, the technical, economic, and policy dimensions jointly shape the long-term feasibility of residential PV systems in Eskisehir. From a technical perspective, the assumed performance parameters, such as the 0.7% annual degradation rate, the performance ratio of 0.80, and system component replacement cycles, directly determine lifetime energy output and thus influence the economic metrics of the LCCA. These technical factors, in turn, interact with key economic outcomes, including the 30-year NPV savings of €883.75, the sensitivity of project viability to discount and inflation rates, and the magnitude of fuel savings. However, these outcomes are highly dependent on Türkiye's evolving regulatory environment. Policies such as net metering, VAT regulations, FiT/FIP mechanisms, and local manufacturing incentives can either amplify or to diminish the financial attractiveness of PV investments by altering both upfront costs and long-term cash flows. The scenario analysis further demonstrates that even modest policy changes can shift the investment from a negative NPV (worst-case scenario) to a significantly favorable one (optimistic scenario). Taken together, these findings show that PV adoption cannot be evaluated through a single lens: technical performance determines the system's physical potential, economic analysis reveals its financial rationality, and policy design provides the enabling framework that ultimately governs consumer adoption. A more integrated approach that links these three dimensions is therefore essential for understanding how residential PV systems can contribute to Türkiye's broader goals of energy security, decarbonization, and sustainable urban development.

4.5. Sensitivity Analysis and Robustness Check

To evaluate the robustness of the economic results, a comprehensive sensitivity analysis was performed on key financial and technical parameters, including discount rate, inflation/electricity price growth, module cost trajectories, system lifespan, end-of-life salvage value, and O&M costs. The results, as displayed in Table 7 and Figure 6, indicate that NPV is most sensitive to discount rate, module cost, and electricity price growth. At the same time, O&M and salvage value have comparatively minor effects. These findings show that supportive financing mechanisms, technological cost reductions, and stable tariff policies can significantly enhance the economic viability of residential PV systems. In contrast, improvements in O&M efficiency yield smaller marginal gains.

Table 7. Sensitivity analysis.

Parameter	Variation Range	Low Case NPV (€)	Base Case NPV (€)	High Case NPV (€)	Impact Level
Discount Rate	7–12%	430	884	1560	High
Inflation	7–12%	610	884	1480	High
Module Cost Change	−20% to +10%	230	884	1540	High
System Lifespan	25–35 years	650	884	1130	Medium
Salvage Value	0–10%	860	884	925	Low
O&M Costs	±30%	760	884	1020	Low

Note: Sensitivity analysis results are calculated by the authors using parameter ranges defined in Section 4.5.

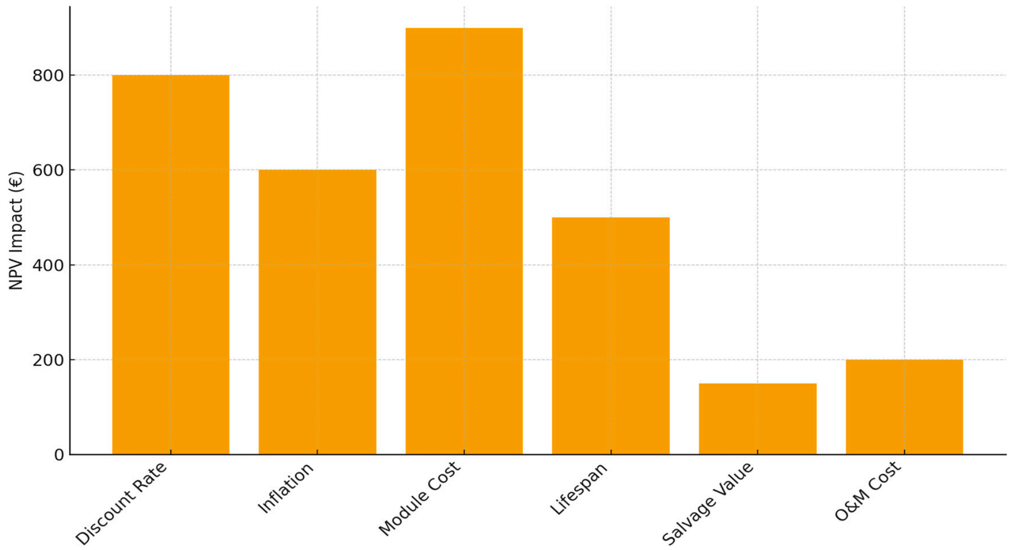

Figure 6. NPV sensitivity chart. Note: This figure is generated by the authors using the sensitivity analysis results presented in Section 4.5.

4.6. PV Performance Degradation

To accurately represent long-term energy generation, an annual linear degradation rate of 0.7% per year was applied to the PV output. This value is consistent with recent empirical studies on mono-crystalline silicon modules deployed in climates similar to those of central Anatolia. The yearly energy output was therefore calculated as in Equation (17) as follows:

$$E_t = E_0 \times (1 - d)^{t-1} \quad (17)$$

where E_0 is the first-year electricity production, d = 0.007 is the degradation rate, and t is the operational year. This approach ensures that cumulative lifetime yields reflect realistic long-term system performance.

4.7. System Boundaries

The life-cycle cost analysis (LCCA) conducted in this study focuses on the economic performance of a 3 kW grid-connected residential photovoltaic system installed in Eskisehir. The system boundaries are defined to include all economic flows directly associated with the installation and operation of the PV system over a 30-year lifetime.

Included processes comprise the acquisition of PV modules, inverters, mounting structures, wiring, balance-of-system components, installation labor, inverter replacement, periodic maintenance, and all economic interactions with the grid through net-metering.

The operational electricity yield is adjusted for both system performance losses and annual degradation.

Excluded processes include upstream manufacturing impacts of PV components, embodied carbon emissions, transportation-related emissions, end-of-life decommissioning, and recycling processes. These aspects are outside the scope of an economic LCCA but are acknowledged as environmental considerations. The study, therefore, reflects a clearly defined 'cradle-to-operation' boundary, focusing exclusively on operational financial performance.

5. Conclusions

This study provides a comprehensive life-cycle cost analysis (LCCA) of photovoltaic (PV) systems within the specific economic and environmental context of Eskisehir, Türkiye, addressing a critical gap in regional analyses of renewable energy adoption in developing countries. Unlike prior studies that often focus on generalized global trends or developed economies, this work incorporates first-hand survey data collected in 2013 alongside updated governmental statistics from TurkStat and CBRT in 2024 to evaluate the long-term financial and ecological feasibility of PV systems. The analysis reveals that PV systems are a rational investment, yielding net present value (NPV) savings of €883.75 over 30 years, despite the initial high costs of installation and maintenance. Beyond the financial advantages, the adoption of PV systems aligns with sustainable development by reducing greenhouse gas emissions, decreasing dependency on fossil fuels, and supporting a cleaner energy transition. This study also emphasizes the importance of government policies, such as feed-in tariffs, tax incentives, and public financing mechanisms, to overcome barriers to adoption and foster the development of a sustainable energy market in Türkiye. Decision-makers are encouraged to use these findings as a guide to enhance renewable energy penetration in local markets while simultaneously addressing energy security and climate goals. This study shows that as a country develops, PV investment costs decline. For instance, with a remarkable difference (around 23% lower than our finding but convenient with our insights), NPV savings of €883.75 through the business-as-usual scenario (however, −€392 under the worst-case and €2350 under the optimistic scenarios) is validated by the 2024 reports of International Renewable Energy Agency (IRENA) which means that this cost difference is needed to be compensated by Turkish Government through an encouragement Feed-in tariff policy for a fair competition with the global weighted average of total installed cost for PV modules.

Future research can explore regional scalability, the integration of alternative renewable energy sources, and the implications of emerging technologies, such as improved energy storage systems, on the financial and environmental performance of PV systems. By contributing to the localized understanding of renewable energy systems, this study provides actionable insights for developing countries aiming to align with global sustainability goals and transition to clean energy. The number of this kind of novel and unique research using economic and financial indicators needs to be increased.

While the present study focuses on the economic dimension of a life-cycle cost analysis, we acknowledge that a full environmental LCCA, covering embodied emissions, CO_2 payback time, and end-of-life ecological impacts, is beyond the scope of the current analysis. Nevertheless, based on established LCCA literature, a 3 kW PV system in Türkiye typically offsets its embodied emissions within 1.5–2 years and reduces lifetime CO_2 emissions by approximately 55–65 tons compared to a natural gas-based energy mix. These environmental benefits complement the economic advantages demonstrated in this study. Future research will integrate environmental LCCA modules directly into the quantitative model.

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Nomenclature

The following abbreviations are used in this manuscript:

A	Initial payment or cost
ALCC	Annualized Life-Cycle Cost
ALCS	Annualized Life-Cycle Savings
A_p	Panel area (m^2)
BAU	Business-as-Usual
C_a	Total area-dependent costs (€/m^2)
CBRT	Central Bank of the Republic of Türkiye
C_e	Total cost of PV equipment which is independent of panel area (€)
C_N	Cost value at Nth period
C_p	Total cost of installed PV equipment (€)
d	Discount rate
ECREEE	ECOWAS Centre for Renewable Energy and Energy Efficiency
EFgrid	Grid emission factor
EPBT	Energy Payback Time
EPV	Electricity generated by the PV system
F_e	Fuel expense
FiPs	Feed-in Premiums
FiTs	Feed-in Tariffs
GHI	Global Horizontal Irradiation
i	Inflation rate
INDC	Intended Nationally Determined Contribution
ITS	Income tax savings
LCCA	Life-Cycle Cost Analysis
LCS	Life-Cycle Savings
m	Mortgage interest rate
M	Initial mortgage principle

M	Mortgage principle
$\mathrm{M_i}$	Maintenance and insurance
$\mathrm{M_p}$	Mortgage payment
NDC	Nationally Determined Contribution
$\mathrm{N_e}$	Term for economic analysis
N_L	Period of mortgage
$\mathrm{N_L}$	Mortgage term
$\mathrm{N_{min}}$	Lesser of $\mathrm{N_L}$ or $\mathrm{N_e}$
NPV	Net present value
O&M	Operation and Maintenance
PEC	Parasitic energy costs
$\mathrm{PP_L}$	Periodic payment of a loan
PT	Property taxes
PV	Photovoltaic
PVGIS	Photovoltaic Geographical Information System
PWF	Present-worth factor
$\mathrm{PW_N}$	Present worth of the Nth payment
REC	Renewable Energy Certificate
ROI	Return on Investment
RPS	Renewable Portfolio Standard
TurkStat	Turkish Statistical Institute
TÜİK	Türkiye İstatistik Kurumu
VAT	Value-Added Tax
$\mathrm{Y_c}$	Yearly cost

Appendix A

Note 1:

For 1 kW/h of energy, 6 modules are needed. Since 1 panel (180 W) is 1.58 m × 0.808 m dimensions and 1.27664 m^2 area, a 6-module area is equal to (i.e., 6 × 1.27664 m^2 = 7.7 m^2) 7.7 m^2. The price of this PV module, which has modules and the necessary equipment, is €2000. A 1 m^2 PV module price is (i.e., from; (€2000 × 1)/7.7 m^2 = €256.7 ≈ €260) €260. The 3 kW PV module area is 23.1 m^2 (i.e., 7.7 m^2 × 3 = 23.1 m^2). Since a 1 kW system needs €250 maintenance cost 3 kW system needs (i.e., from; €250 × 3 = €750) €750 maintenance cost and since 1 kW system needs €200 inverter cost, 3 kW system needs (i.e., €200 × 3 = €600) €600 inverter cost. Thus, according to Equation (1), the total cost of equipment is approximately €7500 (i.e., €260 × 23.1 + (€750 + €600) = €7356 ≈ €7500).

Note 2:

$\mathrm{PW_{15}}$= €250 × $(1 + 0.09)^{14}/(1 + 0.10)^{15}$ ≈ €200

Note 3:

From Equation (13),

PW = €250 × (1/(0.10 − 0.09)) × $(1 - (1.09/1.10)^{30})$ ≈ €5991.25

So, the present worth of the 30-year series is €5991.25.

Note 4:

€6375/PWF(30, 0, 0.10) ≈ €6375/9.43 ≈ €678.25

Note 5:

One should remember that the interest charge varies over time, because the mortgage payment includes both principal and interest. For our example, the interest payment for the first year is (i.e., 0.1 × €6375 = €637.5) €637.5. The annual payment is €678.25; thus, the principal payment is reduced by (i.e., €678.25 − €637.5 = €40.75) €40.75 to (i.e., €6334.25 × 0.10 = €633.425 ≈ €633.5) €633.5 and the principal payment is reduced by (i.e., €678.25 − €633.5 = €44.75) €44.75 to (i.e., €6334.25 − €44.75 = €6289.5) €6289.5. These are indicated in the following Table 2 (to the nearest €).

Note 6:
Here $N_L = N_e$ = 30 years, m = 0.1, d = 0.1, N_{min} = Lesser of N_L or N_e, M = €6375, PWF(N_{min}, 0, d) → PWF(30, 0, 0.1) ≈ 9.4, PWF(N_L, 0, m) → PWF(30, 0, 0.1) ≈ 9.4, PWF(N_{min}, m, d) → PWF(30, 0.1, 0.1) ≈ 27.3.
$PW_{int} = €6375 \times \left[\frac{9.4}{9.4} + 27.3 \times \left(0.1 - \frac{1}{9.4}\right)\right] \rightarrow €6375 \times [0.83] \approx €5291.25$
Note that, while the worth of the interest payments is €5283.25 in Table 2, it is algebraically found as €5291.25. These two values are very close numerically. We can accept that the worth of the interest payment is around €5250. However, the sensitivity of digits, in other words, following the nearest first digit logic, creates this small difference!
Note 7:
year 1:
Interest = 0.10 × €6750 = €675
Principal payment = €715.75 − €675 = €40.75
Principal balance = €6750 − €40.75 = €6709.25
Tax savings = 0.45 × (€675 + €41.75) ≈ €322.5
year 2:
Interest = 0.10 × €6709.25 ≈ €671
Principal payment = €715.75 − €671 = €44.75
Principal balance = €6709.25 − €44.75 = €6664.5
Tax savings = 0.45 × (€671 + €41.75 × $(1.07)^1$ ≈ €322

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