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Techno-economic assessment of a third-party ownership power purchase agreement model for residential rooftop photovoltaics in Egypt

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Abstract
Egypt has significant solar energy potential, creating substantial opportunities for residential rooftop photovoltaic (PV) systems. However, their adoption remains challenging due to high upfront costs and subsidised electricity tariffs, highlighting the need for alternative financing models. This study assesses the viability of the third-party ownership (TPO) model via a power purchase agreement (PPA) to promote residential rooftop PV in Egypt. A techno-economic analysis using PV simulation models was performed for a range of residential electricity consumption profiles. System performance was evaluated over a 25-year project lifetime using key indicators, including capital expenditure (CAPEX), operating expenditure (OPEX), levelized cost of electricity (LCOE), net present value (NPV), internal rate of return (IRR), and customer electricity bill savings. The results indicate that the proposed PV systems achieved strong technical and economic performance. However, the financial viability of the PPA model varied significantly across customer segments. The medium-consumption profile was not financially attractive under the prevailing electricity tariff structure, requiring a PPA price above the grid tariff to achieve acceptable investor returns. In contrast, high-consumption households generated positive NPVs and IRRs exceeding the discount rate, while enabling customer savings of up to 19% relative to grid electricity prices. The findings suggest that PPA-based rooftop PV deployment in Egypt is most viable for high-consumption residential customers and could provide an effective pathway for expanding distributed solar generation while reducing barriers associated with upfront investment costs.

Keywords: Residential rooftop photovoltaic (PV); Power purchase agreement (PPA); Third-party ownership (TPO); Egypt; Business models.

1. Introduction
The global transition to renewable energy is becoming increasingly important as countries face the challenges of climate change, energy insecurity, and growing energy demand. This transition is essential for reducing reliance on fossil fuels, lowering greenhouse gas emissions, and mitigating the impacts of global warming. Fossil fuels are the primary source of global GHG emissions, contributing approximately 64%, mainly from energy-related activities such as electricity generation, transportation, and industrial processes (IPCC, 2023). It is essential to have a substantial reduction in fossil fuel consumption to limit global warming below 2°C (IPCC, 2023).

Since 2024 was the warmest year ever recorded globally, surpassing the previous record set in 2023 (NOAA, 2025), some countries may struggle to balance energy supply and demand as rising temperatures drive higher electricity consumption for cooling purposes. For example, Egypt continues to face challenges in balancing energy supply and demand due to rising consumption, climatic conditions and heavy reliance on fossil fuel power plants (SIS, 2024). By integrating solar, wind, and other renewable sources, countries can better manage supply risks while providing clean, sustainable alternatives to fossil fuels, thereby helping reduce greenhouse gas emissions.

Egypt possesses significant solar energy potential, making solar power one of the country's most promising renewable energy resources. Its geographic location provides some of the highest solar irradiance levels globally, creating highly favourable conditions for photovoltaic (PV) electricity generation. The global horizontal irradiance (GHI) ranges from 5.25 to 6.71 kWh/m^2/day, with an average of 6.26 kWh/m^2/day (ESMAP, 2020). In addition, Egypt receives approximately 3,050 hours of sunshine annually (Moharram et al., 2022). These abundant solar resources enable efficient PV power generation and provide substantial opportunities to meet growing domestic electricity demand, enhance energy security, support sustainable development, and potentially facilitate electricity exports.

In recent years, the Egyptian government has introduced a series of incentives, including net metering policies, feed-in tariffs, and tax exemptions, to promote the adoption of distributed solar energy systems (Abouaiana and Battisti, 2025). As of 2024, Egypt's total renewable energy capacity was 7,752 MW, accounting for 12.7% of total electricity capacity compared to 8.4% in 2017 (IRENA, 2025). The country's solar energy capacity increased to 2,590 MW in 2024, up from 180 MW in 2017 (IRENA, 2025). Wind energy capacity also increased to 2,199 MW in 2024, up from 755 MW in 2017 (IRENA, 2025). Meanwhile, hydropower capacity has remained steady at 2,832 MW since 2018 (IRENA, 2025). A major contributor to Egypt's solar expansion is the Benban Solar Park, with a total installed capacity of 1.8 GW and among the largest solar parks in the world (Masdar, n.d.). As a result of continued renewable energy development, Egypt has become the second-largest solar energy producer in Africa (IRENA, 2025). Despite this progress, further expansion of renewable energy capacity is required to achieve the country's long-term energy objectives. Egypt aims to increase the share of renewable energy in its electricity mix to 42% by 2035, including 25% from solar energy (Moharram et al., 2022). However, the government has revised its 2040 renewable energy target downward from 58% to 40%, indicating that natural gas is expected to remain a vital component of the country's future energy strategy (Reuters, 2024).

Large-scale assessments indicate that global rooftop PV resources are sufficient to generate tens of petawatt-hours of electricity annually, reinforcing their critical role in deep decarbonisation pathways and long-term climate mitigation strategies (Joshi et al., 2021). In Egypt, high solar irradiation levels could enable large-scale rooftop PV deployment, reducing reliance on natural gas-fired generation, enhancing energy security, and supporting national decarbonisation and energy diversification. The widespread deployment of rooftop solar PV has the potential to substantially reduce carbon footprints and play a critical role in mitigating global warming (Zhang et al., 2025), but key barriers to solar PV adoption in developing countries include financial constraints, weak policy frameworks, low technological and environmental awareness, limited institutional support, market instability, and other contributing factors (Mustafa et al., 2024). Also, one of the most global challenges is the high initial capital cost associated with rooftop PV installations. Even as the cost per watt of solar modules has dropped significantly over the past decade (Hajdukovic, 2022), upfront system costs, including installation and maintenance, remain prohibitive for many households—especially in developing nations without subsidized financing or credit systems (Yadav et al., 2019).

Energy in Egypt has historically been subsidised. However, the sector is currently undergoing significant structural reforms, including the gradual reduction of electricity subsidies. As part of an $8 billion financial support programme, the International Monetary Fund (IMF) has required Egypt to implement subsidy cuts to improve fiscal sustainability (Reuters, 2025). Residential electricity tariffs under the current subsidy structure are summarised in the supplementary material, which shows that the tariff structure is progressive, resulting in significant differences in electricity costs across residential consumption levels.

As discussed, the high cost of solar PV modules poses a significant economic challenge for developing countries, underscoring the need for innovative business models to support rooftop PV deployment in contexts such as Egypt. A range of global business models exists, including self-ownership, community solar, Third-Party Ownership (TPO), Power Purchase Agreements (PPAs), solar leasing, store-on-grid, peer-to-peer, and equity-focused models, as summarized and further explained in the supplementary material. Among these, self-ownership and third-party ownership are the dominant approaches in countries such as Germany and Japan, as well as in several U.S. states (Rathore et al., 2019). However, these models may not be directly transferable to other contexts due to differences in market structures and economic conditions.

Understanding the techno-economic feasibility of rooftop PV systems and associated business models under the current subsidy structure in Egypt is therefore essential for unlocking business opportunities and scaling rooftop PV deployment. Furthermore, evaluating how different business models perform under this policy environment can help identify financially viable pathways for both consumers and investors. This, in turn, is critical for accelerating rooftop PV adoption and supporting Egypt's energy transition objectives.

1.1. Objective of the paper

The objective of this study is to evaluate the potential of the TPO model, particularly PPAs, to support the deployment of residential rooftop PV systems in Egypt under the current electricity tariff structure.Specifically, this study aims to:

- Assess the techno-economic performance of residential rooftop PV systems as a baseline for evaluating the TPO/PPA business model.
- Investigate the applicability of the TPO model for residential rooftop PV deployment in Egypt, by evaluating the financial performance of the PPA model across different residential electricity consumption profiles.
- Identify PPA electricity selling prices that provide economic benefits for both consumers and investors.

2. Literature review

This section explores the techno-economic feasibility of rooftop PV solar systems in Egypt and the associated global innovative business models in this multifaceted topic that intersects economic, technical, and policy dimensions. These factors often vary significantly across regions, requiring a thorough and context-sensitive analysis. To ensure a comprehensive and rigorous examination of the existing body of research, a systematic review methodology (Snyder, 2019) was employed. This approach enables the structured identification, selection, and synthesis of relevant studies, allowing for a clear understanding of current knowledge and gaps in the literature.

2.1. Review methodology

The literature search strategy focused on English-language studies published between 2020 and 2025 to capture the most recent data on PV module costs and their economic feasibility. For the business model analysis, the review period was extended to 2019–2025 to capture a broader range of implementation experiences. The review prioritized

peer-reviewed journal articles, conference proceedings, reports, and theses, while excluding utility-scale solar projects, books, and non-English sources.
The primary academic research was conducted through the Victoria University of Wellington library, while the data collection focused on the ScienceDirect and Scopus databases, supplemented by searches on Google Scholar. Search terms included combinations of keywords such as "rooftop PV", "rooftop photovoltaics", "rooftop solar", "Egypt", and "business models". The detailed search strategy is provided in the Supplementary Material.

Study selection followed the PRISMA approach (Moher et al., 2009). After removing duplicate records, titles, keywords, abstracts, and full texts were screened against predefined inclusion and exclusion criteria. The PRISMA flow diagram detailing the study selection process is presented in the Supplementary Material. Data were extracted on techno-economic feasibility, including the impacts of electricity subsidies, financial viability, and policy uncertainty, as well as on business models and adoption drivers. The findings were synthesized using a narrative approach and organized into two themes: (1) evaluating technical feasibility and economic aspects within the Egyptian context, and (2) business models and adoption drivers.

2.2. Key themes in the literature

2.2.1. Evaluating technical feasibility and economic aspects within the Egyptian context.

Several techno-economic studies have assessed the feasibility of rooftop PV in Egypt using simulation tools and software such as HOMER, PVGIS, PVsyst, and MATLAB. These investigations primarily focus on optimizing system sizing, evaluating energy yield, and analysing key financial indicators such as Net Present Value (NPV), Internal Rate of Return (IRR), and the Levelized Cost of Electricity (LCOE). Furthermore, a dimension of these studies involves site selection and spatial suitability analysis, often utilizing Geographic Information Systems (GIS).

Sadeq et al. (2020) evaluated the suitability of rooftop PV systems across four Egyptian cities and found that Aswan offered the highest solar energy potential and the most favourable economic performance compared to Cairo, Alexandria, and Hurghada. The study highlighted the importance of geographic and climatic conditions in influencing the technical and economic feasibility of PV systems and emphasized the value of location-specific assessments for investment decision-making.

A study by Awad et al. (2022) demonstrated that advanced optimization techniques can improve the technical and economic feasibility of rooftop PV systems. Using Particle Swarm Optimization (PSO) and load forecasting models for Assiut University's campus, the study identified an optimal PV system size that was validated using PVsyst and PVGIS. The results showed that PSO provided accurate and cost-effective sizing while accommodating future growth in electricity demand.

Muhammed et al. (2021) developed a city-scale methodology for assessing rooftop PV potential by combining satellite imagery analysis with PV generation estimation tools. Applied to Madinaty in Cairo, the approach achieved high rooftop detection accuracy and identified substantial rooftop areas suitable for PV deployment. The findings indicated that rooftop PV systems could provide significant environmental benefits, including offsetting approximately 48% of annual CO_2 emissions, while highlighting the effectiveness of GIS-based tools for evaluating technical PV potential.

Long-term outdoor performance of PV technologies under Cairo's climatic conditions has shown that commercial simulation tools can reliably predict annual energy production, although their accuracy is lower for monthly estimates. Differences in degradation rates and temperature sensitivity were also observed among PV technologies, highlighting the need for improved performance modelling for hot and arid environments (Othman and Hatem, 2022).

Techno-economic assessments have also demonstrated the potential of rooftop PV systems in industrial applications. An evaluation of a 130 kWp grid-connected PV system for a factory in Al Obour City showed annual electricity generation of 212.7 MWh and a 20% reduction in electricity costs, confirming both the technical viability of the system and the effectiveness of PVsyst as a design and performance assessment tool (Moustafa et al., 2024).

The integration of rooftop PV systems with passive building design strategies has been shown to enhance both energy efficiency and sustainability. Using the “Sakan Masr” housing project as a case study, the combination of passive design measures and east–west-oriented PV arrays increased electricity generation by 14%, reduced cooling demand, and delivered greater cost and emissions savings compared with conventional south-facing PV installations (Raslan et al., 2025).

Hybrid energy systems combining PV, battery storage, and diesel generators have also demonstrated significant technical and environmental benefits. A study at the Aswan campus of AASTMT found that optimized PV-based configurations reduced grid electricity consumption by 38%, lowered emissions by 50%, and decreased the levelized cost of energy (LCOE). Although dual-axis tracking improved energy output, it was associated with higher costs, highlighting the trade-off between performance and economic viability (Abd Elsadek et al., 2024).

The feasibility of residential PV systems can be assessed through financial indicators such as NPV, levelized cost of energy (LCOE), payback period, and electricity bill savings. Household energy consumption patterns, the structure of incentive policies, and key financial variables, including system costs and interest rates, drive economic performance. A study by Gabr et al. (2020) showed that although rooftop PV systems present strong potential in the residential sector, their viability remains sensitive to user demand profiles and supportive policy frameworks.

A study on rural Egyptian buildings examined energy-use intensity and the potential of rooftop PV systems, showing that electricity consumption is strongly influenced by household lifestyle, family size, and building characteristics, with an average consumption of 22 kWh/m^2 per year. While rooftop PV systems demonstrated substantial generation potential, the analysis found they are not yet economically viable under current conditions, underscoring the need for supportive policy measures to enable rural energy transitions (Abouaiana and Battisti, 2025).

Senyonyi et al. (2025) evaluated rooftop and façade integration of PV and wind systems in Egypt, showing that PV, particularly on south-facing façades, delivers the highest energy output, lowest LCOE, and greatest CO_2 savings. Wind-only systems performed poorly, while hybrid PV–wind turbine models achieved moderate efficiency and feasibility. These findings emphasize the clear economic and environmental advantages of PV for sustainable building design.

Research on public buildings by Najeeb et al. (2025) examined the feasibility of installing small-scale PV stations on school rooftops with unused roof space. Using simulation tools such as PVsyst and Skelion, the analysis identified optimal panel inclination angles (18–22°) and spacing to minimize shading and maximize output. Further analysis of public and religious buildings by Najeeb et al. (2024) considered site conditions, building dimensions, solar angles, and climatic factors using tools such as PVsyst, Skelion, and Google Earth. Findings indicate that rooftop PV on 31,290 schools could generate between 8,448 and 14,080 MWh annually.

A study at the Electronics Research Institute in Cairo assessed the performance of a grid-connected rooftop PV system using year-long real-time monitoring (Hassan et al., 2024). The system achieved an average annual efficiency of 15.8%, a performance ratio of 83%, and a capacity factor of 18.7%, with yields highest in summer and lowest in winter.

At the university level, a 105 kW_p rooftop PV system was installed at the Faculty of Engineering, Zagazig University (Azab et al., 2023). Using NREL SAM for performance and financial optimization, the system achieved an annual production of 175,700 kWh, a capacity factor of 19.1%, and grid parity at 0.55 EGP/kWh, with a payback period of 7.9 years and lifetime CO_2 savings of 1,882 tons.

At the urban scale, rooftop PV potential in the residential project Madinaty in Cairo was estimated using a two-stage approach combining satellite image detection and machine learning (SVM and Naïve Bayes) with PV potential calculators PVWatts, PVGIS, and ArcGIS (Muhammed et al., 2023). Approximately 290 rooftops were identified, with an annual PV generation potential of 21–25 GWh, reducing CO_2 emissions by around 62%.

The technical and economic impacts of grid-connected PV–battery systems in Egypt were also evaluated under existing incentive policies (Gabr et al., 2021). MATLAB simulations showed that net energy metering (NEM) and feed-in-tariff (FiT) schemes significantly affect system sizing, self-sufficiency, and financial returns, with battery storage enhancing grid independence. The results indicate that optimizing both system size and increasing incentives can maximize profitability and reduce reliance on the utility grid, highlighting the importance of policy design for residential rooftop PV deployment.

Finally, an industrial-scale case study assessed the performance of a 126 kWp rooftop PV system installed at the HIKMA-Pharma factory in Giza city (Ibrahim et al., 2018). Using PVsyst and SketchUp simulations, the system produced 237 MWh/year with a performance ratio of 81.7%, injecting 227 MWh/year into the grid over its 30-year lifetime. An economic analysis showed that the system could reduce total energy costs by 53% compared with diesel and grid electricity, achieving payback in approximately seven years. These findings underscore the technical and financial feasibility of large-scale rooftop PV for industrial buildings in Egypt.

2.2.2. Business models and adoption drivers

Numerous studies have been conducted globally on various business models, which differ from one country to another due to each market's unique combination of economic, regulatory, social, and technical factors.

Previous studies have identified self-ownership and TPO as key business models driving residential PV deployment in developed solar markets, including Germany, Japan, and several U.S. states (Rathore et al., 2019). In Germany and Japan, self-ownership is widely adopted (Yamashiro and Mori, 2023), with more than 70% of PV systems in Germany installed on residential rooftops (Rathore et al., 2019), largely because consumers can afford the upfront investment.

Apart from financial constraints in PV deployment, other important considerations include grid access and reliability. Some grid operators prioritize stability and reliability over resilience. For example, on Miyakojima Island in Japan, a third-party ownership and aggregation business model proved attractive, as private companies installed and managed PV systems while aggregating demand response for customers, providing the grid operator with much-needed flexibility (Yamashiro and Mori, 2023).

In India, self-owned and third-party ownership models are commonly used for rooftop solar PV, accounting for approximately 75% and 25% of the market, respectively (Rathore et al., 2019). In contrast, the utility-owned model has not gained traction, primarily due to the absence of supportive government policies and the relatively low profit margins compared to ground-mounted PV power plants (Rathore et al., 2019).
In markets such as Switzerland, where a large proportion of the population is tenants, the community solar business model has proven attractive to consumers, regardless of the technology used, whether Building-Integrated Photovoltaics or conventional solar panels (Stauch and Vuichard, 2019).

Consumer behaviour and regulatory contexts play a critical role in rooftop PV adoption. A study in Indonesia by Pramana et al. (2024) examined consumer responses to rooftop PV and other innovative energy services, showing that personal norms, social influence, and regulation strongly shape purchase intentions. The findings highlight a high demand for future energy services and emphasize the need for energy firms to adapt strategies according to consumer behaviour and regulatory requirements to support the renewable energy transition.

Malaysia's solar PV sector has expanded significantly under feed-in tariffs and renewable energy policies, although policy shifts and quota constraints have introduced market challenges. New frameworks such as self-consumption schemes, net energy metering, and financing options have reshaped business models and supported continued market growth. Despite COVID-19 disruptions, the sector remained resilient, with rising installation capacity driven by supportive policies and flexible financing mechanisms, offering important insights for policymakers and investors (Koerner et al., 2022).

In Sub-Saharan Africa, the store-on-grid (SoG) model was evaluated across 13 countries, showing that it is viable in nine countries under lower PV prices, but only in four under higher prices (Mukisa et al., 2021). High lending rates emerged as a significant barrier to adoption. The study notes that while feed-in tariffs and net-metering have successfully supported renewable energy in developed regions, their absence in many developing countries forces PV projects to rely solely on self-consumption, limiting financial incentives. Therefore, the SoG scheme presents an attractive business model in contexts where feed-in tariffs and net-metering are not supported.

Iran, with strong solar potential, offers another example of model adaptation. Heirani et al. (2022) assessed business models for distributed solar PV (DSPV) through literature review and expert interviews on key barriers. The findings indicate that a customer/third-party ownership model with utility control is most suitable. The study also outlines the roles and interactions of key stakeholders in promoting DSPV development.

Shared and community systems have proven effective in urban residential contexts. In India, rooftop solar models for high-rise apartments were compared, revealing that a centralized community system with upfront financing provides the lowest cost and fastest payback, further improved by subsidies (Kumar et al., 2023). These results highlight the financial viability of shared rooftop solar models and guide customers, developers, and policymakers in urban settings.

Community solar adoption has also evolved in developed markets. A review of England's community energy business models examined community solar PV projects, noting how these models adapted following the withdrawal of government subsidies (Nolden et al., 2020). The study identified three key business model archetypes and analysed their development through the lenses of science and technology studies and transaction cost economics. It also highlighted the emerging role of intermediary actors in creating more complex, contract-based structures that can sustain and expand community participation in a post-subsidy environment.

Emerging peer-to-peer (P2P) energy trading models offer innovative pathways for rooftop PV adoption. In Thailand, P2P energy trading was investigated, driven by declining PV costs and technology advancement (Junlakarn et al., 2022). Using the PESTLE framework, the study identified key drivers and barriers and provided policy recommendations to support P2P market growth. These recommendations include ensuring third-party access to energy platforms, establishing clear legal recognition and integration of prosumers into the energy market, creating standardized rules for energy transactions, and implementing incentives that encourage households and businesses to participate actively in decentralized energy trading, thereby fostering a more flexible, efficient, and consumer-driven renewable energy ecosystem. Similarly, Klein et al. (2019) tested a P2P energy-sharing model in Portugal under real market conditions. The study showed that local sharing of surplus PV electricity among users connected to the same transformer can yield financial benefits, despite regulatory barriers, contributing to a more consumer-centric and flexible energy system.

Equity-focused business models have also emerged in the U.S., where policy interventions and tailored financing approaches have increased rooftop PV adoption among low- and moderate-income (LMI) households (O'Shaughnessy et al., 2021). Mechanisms such as LMI-targeted financial incentives, leasing options, and property-assessed financing expanded access in underserved communities and generated peer effects that further increase adoption. These findings suggest that policy-driven business models can balance deployment patterns and make solar energy benefits more equitable across income groups.

Collectively, these studies illustrate that effective rooftop PV business models should consider consumer behaviour, regulatory frameworks, financial mechanisms, and technological innovations. The diversity of approaches demonstrates the need for context-specific adaptation. For emerging markets like Egypt, these international lessons provide actionable insights for designing innovative business models that support large-scale rooftop PV adoption while addressing economic, social, and environmental objectives.

2.3. Literature review conclusion

This review highlights the significant potential of rooftop PV systems in Egypt, while also revealing gaps in understanding how to translate this potential into widespread adoption. The technical feasibility of rooftop PV is well established, with studies demonstrating favourable solar irradiance levels, competitive levelized costs of energy, and reliable system performance across multiple Egyptian cities. However, most of the literature focuses on technical aspects, with limited research on the practical deployment strategies and adoption pathways needed to achieve large-scale implementation in Egypt. International experiences demonstrate that innovative business models, such as third-party ownership, community solar, and peer-to-peer energy trading, combined with supportive policy frameworks, can significantly accelerate rooftop PV deployment.

3. Research methods

This section presents the methodology used to assess the suitability of rooftop PV deployment in Egypt, focusing on the TPO model, specifically the PPA framework. A simulation-based techno-economic approach is adopted to evaluate system sizing, energy performance, and financial feasibility for residential applications.

The analysis involves modelling multiple PV system configurations under the PPA scheme, incorporating a range of residential load profiles to capture variations in household electricity consumption. The performance of each configuration is assessed using key economic indicators, including net present value (NPV), levelized cost of electricity (LCOE), Internal Rate of Return (IRR), and electricity bill savings. This framework enables a robust evaluation of the PPA model's potential to facilitate rooftop PV adoption in Egypt by reducing upfront capital requirements while maintaining financial viability for both investors and end users.

3.1. Site selection

Cairo was selected as the representative study location due to its high urban density and strong solar resource potential, with an average Global Horizontal Irradiance (GHI) of 5.763 kWh/m^2/day (ESMAP, 2020). A multi-residential building in Madinaty, Cairo (30.096655° N, 31.662533° E), was selected as the case study site. As discussed in the literature review, Madinaty offers a substantial rooftop area suitable for PV deployment and has significant potential for solar energy generation.

3.2. Data collection

3.2.1. Solar data

Solar resource data were obtained from the Meteonorm database through PVsyst. Meteonorm provides long-term meteorological data, including solar irradiation and climatic parameters, for specific geographic locations. Weather data corresponding to the selected study site in Cairo, Egypt, were used to represent local solar and climatic conditions. These data served as the primary inputs for simulating PV system performance and estimating annual electricity generation.

3.2.2. Household load profiles

Electricity consumption data were obtained from seasonal residential load profiles developed in a previous study by Sayed (2024). These profiles represent typical variations in household electricity demand throughout the year and were used to model residential consumption patterns under different usage levels.

The analysis in this paper focused on medium- and high-consumption households. The low-consumption category was excluded because these consumers benefit from substantial electricity subsidies, which can significantly distort the economic assessment of rooftop PV systems. One medium-consumption load profile was included in the analysis. As the high-consumption category covered a wide range of electricity usage levels, two representative profiles were selected and designated as High-Consumption A and High-Consumption B to capture variations within this consumer segment.

3.2.3. Economic input data

Cost data, including capital expenditure (CAPEX) and operational expenditure (OPEX), were obtained through a market survey of PV system suppliers and service providers in Egypt. All cost and tariff data were converted from Egyptian Pounds (EGP) to U.S. Dollars (USD) using the average exchange rate reported by the Central Bank of Egypt for 2025 (CBE, 2026). The collected cost data were then scaled according to the PV system size considered in the analysis. Financial parameters, including the discount rate and inflation rate, were obtained from official publications of the Central Bank of Egypt (CBE, 2026), while the residential electricity tariff structure was sourced from the Egyptian Electric Utility and Consumer Protection Regulatory Agency (EgyptERA, 2024).

3.3. System configuration and scenario design

A grid-connected rooftop PV system without battery storage was modelled for all household load profiles considered in this study. The system operates in parallel with the utility grid, with electricity generated by the PV system first used to meet household demand, and the grid supplying any remaining demand. Surplus electricity is exported to the grid under Egypt's net energy metering (NEM) scheme, with energy credits offset against consumption and settled at the end of the fiscal year (EgyptERA, 2020). In accordance with Egyptian regulations, the PV systems were sized so that the estimated annual electricity generation did not exceed the consumer's annual electricity consumption (EgyptERA, 2020). However, minor deviations may occur due to the discrete sizing of PV systems.

To evaluate the feasibility of the PPA model, multiple scenarios were developed using different residential load profiles and electricity selling prices. The technical performance of the PV systems and the financial outcomes for both investors and consumers were assessed under each scenario using key economic indicators, including NPV, LCOE, IRR, and user electricity bill savings.

Comparing these scenarios enables an assessment of how variations in household electricity consumption and PPA pricing influence the economic viability of rooftop PV deployment in the Egyptian residential sector.

3.4. Economic analysis

The economic analysis is conducted from two complementary perspectives: (1) the solar service provider (investor), who owns, operates, and maintains the rooftop PV system and sells the generated electricity under a long-term contractual arrangement; and (2) the electricity consumer, who benefits from reduced electricity expenditures through the PPA. The financial performance of each system configuration is evaluated using standard investment appraisal methods, including LCOE (Nieto-Díaz et al., 2021), NPV, and IRR

(Short et al., 1995). These indicators are used to assess the cost-effectiveness of the PPA model and its ability to offer electricity at competitive prices compared to conventional grid tariffs.

The LCOE is defined as the average cost of generating one kilowatt-hour (kWh) of electricity over the system lifetime and is expressed as:

$$LCOE = \frac{I_0 + \sum_{t=1}^{l} \frac{C_t}{(1+d)^t}}{\sum_{t=1}^{l} \frac{E_t}{(1+d)^t}} \tag{1}$$

Where:
I_0 is the installation cost (initial capital investment);
C_t are the total cost in year t;
E_t is the electricity generation in year t;
d is the discount rate; and
l is the project lifetime.

3.5. PPA model

3.5.1. Investor's perspective (seller)

From the investor's perspective, revenue is generated by selling electricity to the end user under the PPA tariff. The investor bears the initial CAPEX and ongoing OPEX. The investor's NPV is calculated as:

$$NPV = \sum_{n=0}^{N} \frac{F_n}{(1+d)^n} \tag{2}$$

Where:
F_n is the net cash flow in year n;
N is the analysis period; and
d is the annual discount rate.

The IRR is also used to evaluate the attractiveness of an investment relative to alternative opportunities.

$$0 = NPV = \sum_{n=0}^{N} \frac{F_n}{(1+d)^n} \tag{3}$$

Where:
NPV is the net present value of the capital investment;
F_n is the cash flow received at time n;
N is the analysis period; and
d is the discount rate that equates the present value of positive and negative cash flows.

3.5.2. Consumer’s perspective (buyer)

From the consumer’s perspective, financial benefit arises from the difference between electricity costs under the PPA scheme and baseline grid electricity expenditures. The annual electricity bill savings are expressed as:

$$S_t = B_{grid} - P_{PPA} \quad (4)$$

Where:
S_t is the annual saving;
B_{grid} is the baseline grid electricity cost without PV; and
P_{PPA} is the annual payment under the PPA agreement.

The model evaluates whether the PPA tariff yields net savings over time relative to grid-only electricity consumption, while ensuring the pricing structure remains economically viable for both the investor and the end user.

3.6. Limitations

- Load profiles may not fully represent actual consumption patterns.
- Market prices and tariffs may change during the study period.
- Net metering regulations and compensation schemes may change over time, affecting financial outcomes.
- Financial parameters such as discount rate and inflation are assumed constant over the project lifetime and may not reflect actual economic volatility.

4. Results and discussion

This section presents and discusses the results of the economic assessment of the PPA model as a TPO business model for residential rooftop PV systems in Egypt. It includes the PV system sizing and economic assessment results, followed by an evaluation of the PPA model under different pricing scenarios over a 25-year project lifetime. Attention is given to the relationship between the PPA selling price, investor profitability, and customer benefits.

The analysis was conducted using a 19.5% discount rate, reflecting the economic conditions relevant to the Egyptian market. Annual OPEX was set at 2% of the initial CAPEX and increased annually by 12.3% in line with the inflation rate. Electricity tariffs were projected to increase by 10% per year throughout the project lifetime. This projection is conservative relative to historical tariff trends, as residential electricity tariffs in Egypt increased by approximately 72% between 2020 and 2025. These inputs were incorporated into the economic analysis to evaluate the long-term financial viability of the PV systems and the proposed business model.

4.1. System design results

4.1.1. Overview of the selected consumption profiles

Three representative electricity consumption profiles were selected. For each profile, a rooftop PV system was designed to generate electricity approximately equal to the household's annual electricity demand. Table 1 presents the annual electricity consumption, selected PV system size, and annual electricity generation for each profile. Detailed daily, weekly, and monthly energy production results generated using PVsyst are provided in the Supplementary Material.

Table 1. Summary of system sizing results

Profile	Annual Electricity Consumption (kWh/year)	PV System Size (kWp)	Annual PV Generation (kWh/year)	Generation-to-Demand Ratio (%)
Medium Consumption	6,353	4	6,503	102.4
High Consumption A	10,002	6	10,006	100.0
High Consumption B	14,034	9	15,050	107.2

The results indicate that the selected PV capacities closely matched the annual electricity demand of the corresponding households. The medium-consumption profile required a 4 kWp system to generate approximately 6,503 kWh annually, slightly exceeding the annual demand of 6,353 kWh. Similarly, the high-consumption profile A required a 6 kWp system, producing approximately 10,006 kWh per year, which closely matched the annual electricity consumption of 10,002 kWh. For the high-consumption profile B, a 9 kWp system was selected, resulting in an annual generation of approximately 15,050 kWh. This generation exceeded the annual electricity demand of 14,034 kWh by approximately 7.2%.

The results demonstrate a direct relationship between household electricity consumption and the required PV system capacity. As annual electricity demand increased from 6,353 kWh to 14,034 kWh, the required system size increased from 4 kWp to 9 kWp. Furthermore, the designed systems achieved annual electricity generation levels that were broadly proportional to household demand, indicating that the sizing methodology successfully matched system capacity to consumption requirements. This is particularly important within the context of a PPA-based TPO model, as system sizing directly affects project capital costs, electricity production, investor returns, and customer benefits.

4.2. Economic analysis of the proposed PV systems

4.2.1. Capital and operating costs

The economic performance of the proposed rooftop PV systems was assessed by using CAPEX and discounted OPEX. The CAPEX represents the initial investment required for system installation, while the discounted OPEX accounts for the operation and maintenance costs incurred throughout the project lifetime. Table 2 summarizes the economic characteristics of the three PV systems.

Table 2. Capital and operating costs of the proposed PV systems

Profile	System Size (kWp)	CAPEX (USD)	Discounted OPEX over 25 Years (USD)
Medium Consumption	4	1,600	350
High Consumption A	6	2,400	526
High Consumption B	9	3,600	789

The capital investment increases with system size. The medium-consumption profile required an initial investment of USD 1,600 for a 4 kWp system, while the 6 kWp and 9 kWp systems required investments of USD 2,400 and USD 3,600, respectively. The increase in CAPEX reflects the larger installed capacity required to meet higher electricity demand. Similarly, the discounted OPEX increased with system size, rising from USD 350 for the medium-consumption profile to USD 789 for the largest system. This trend is consistent with the increased maintenance and operational requirements associated with larger PV installations.

4.2.2. Levelized cost of electricity analysis

The LCOE was calculated to determine the lifetime cost of electricity generation for each PV system. As a widely used indicator in renewable energy assessments, it enables comparison of electricity generation costs across different system sizes and configurations. Table 3 summarizes the LCOE of the three PV systems.

Table 3. LCOE results for the proposed PV systems

Profile	LCOE (c/kWh)
Medium Consumption	1.28
High Consumption A	1.24
High Consumption B	1.22

The results indicate a gradual reduction in LCOE as system size increases. The medium-consumption profile exhibited the highest LCOE at 1.28 c/kWh, while the 9 kWp system associated with the high-consumption profile B achieved the lowest value at 1.22 c/kWh. The reduction in LCOE can be attributed primarily to economies of scale. Although larger systems require higher initial investments, they also generate significantly more electricity over their operational lifetime. Consequently, the total project costs are distributed over a larger energy output, resulting in a lower unit cost of electricity generation.

The small variation in LCOE among the three profiles indicates that all proposed systems can generate electricity at a comparable cost. Nevertheless, the lower LCOE values associated with the larger systems suggest a slight economic advantage for high-consumption households within a PPA framework. Lower generation costs provide greater flexibility in setting electricity selling prices while maintaining acceptable financial returns for the TPO provider. The LCOE results provide an initial indication that larger residential rooftop PV systems may offer improved economic performance and may represent attractive target segments for future PPA-based business model deployment in Egypt.

4.3. Financial performance of the PPA model

4.3.1. Base Scenario: PPA price equal to the applicable grid tariff

In the base scenario, the electricity selling price under the PPA was assumed to be equal to the applicable residential grid tariff for each consumption profile. In this model, the TPO finances, owns, and operates the PV system, bearing all associated capital and operating costs, while the customer purchases the generated electricity without incurring any upfront costs. The financial performance of the proposed projects was evaluated using NPV and IRR. The results are presented in Table 4.

Table 4. Financial performance of the base PPA scenario

Profile	PPA Price (c/kWh)	NPV (USD)	IRR (%)
Medium Consumption	2.92	-235	16.9
High Consumption A	4.20	662	23.9
High Consumption B	4.46	1,124	24.3

The results indicate substantial differences in project feasibility across the consumption profiles examined. For the medium-consumption profile, the project generated a negative NPV of USD 235 and an IRR of 16.9%, which is below the 19.5% discount rate. Consequently, the project cannot be considered financially attractive from the perspective of the TPO investor under the assumed conditions. In contrast, both high-consumption profiles yielded positive NPVs and IRRs that exceeded the discount rate. High Consumption A achieved an NPV of USD 662 and an IRR of 23.9%, while High Consumption B generated an NPV of USD 1,124 and an IRR of 24.3%. These results indicate that the proposed PPA model is financially feasible for households with higher electricity consumption levels.

4.3.2. Sensitivity analysis of PPA selling price for medium-consumption profile

A sensitivity analysis was performed to examine the impact of the PPA selling price on the financial performance of the medium-consumption profile. The results are presented in Figure 1.

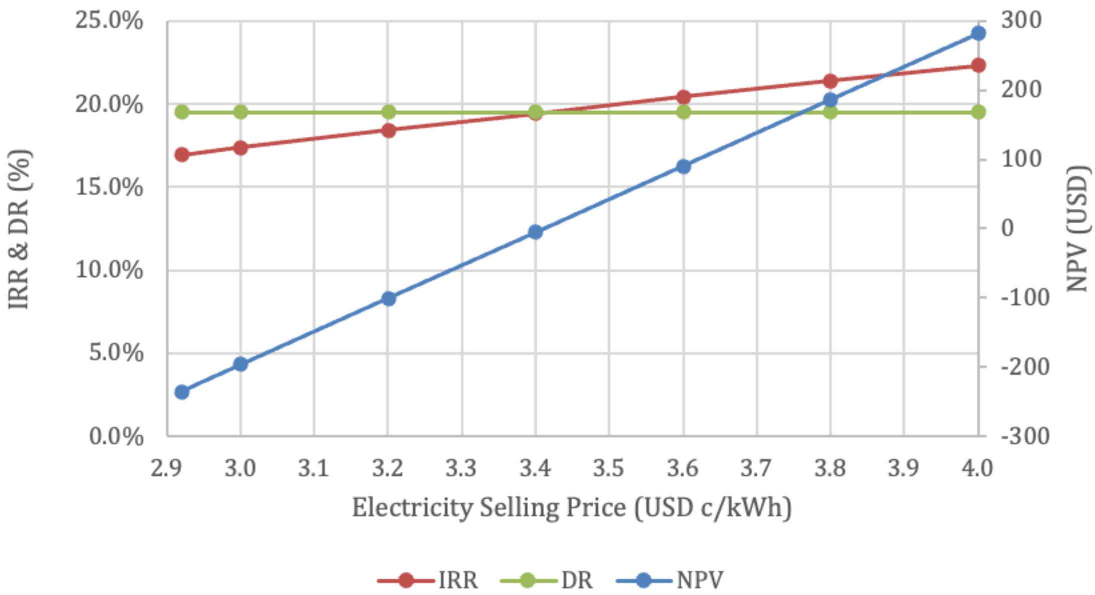

Figure 1. Impact of electricity selling price on NPV and IRR

The results indicate a strong positive relationship between the PPA selling price and project profitability. As the selling price increased from 2.92 c/kWh to 4.00 c/kWh, the project NPV increased from -235.9 USD to 282.0 USD, while the IRR increased from 16.9% to 22.3%.

At the applicable residential tariff of 2.92 c/kWh, the project generated a negative NPV and an IRR below the 19.5% discount rate, indicating it is not financially viable for the TPO investor. Increasing the selling price improved financial performance; however, the project only approached financial feasibility at approximately 3.40 c/kWh, with an NPV close to zero and an IRR of 19.4%. A selling price of approximately 3.40 c/kWh represents the break-even threshold for the medium-consumption profile. This value is approximately 16% higher than the applicable grid tariff. Consequently, the PPA provider would need to charge a tariff higher than the prevailing electricity price to achieve acceptable investment returns. These findings suggest that households with medium consumption may not be an attractive market segment for PPA-based rooftop PV deployment under current tariff conditions in Egypt. Also, revenue from electricity sales is insufficient to cover project costs while maintaining a competitive electricity price for consumers.

4.3.3. Sensitivity analysis of PPA selling price for high consumption profile A

A sensitivity analysis was conducted to evaluate the effect of the PPA selling price on investor profitability and customer savings for high consumption profile A. The PPA selling price was gradually reduced below the applicable grid tariff of 4.2 c/kWh, and the resulting changes in NPV, IRR, and customer savings were assessed. The results are presented in Figures 2 and 3.

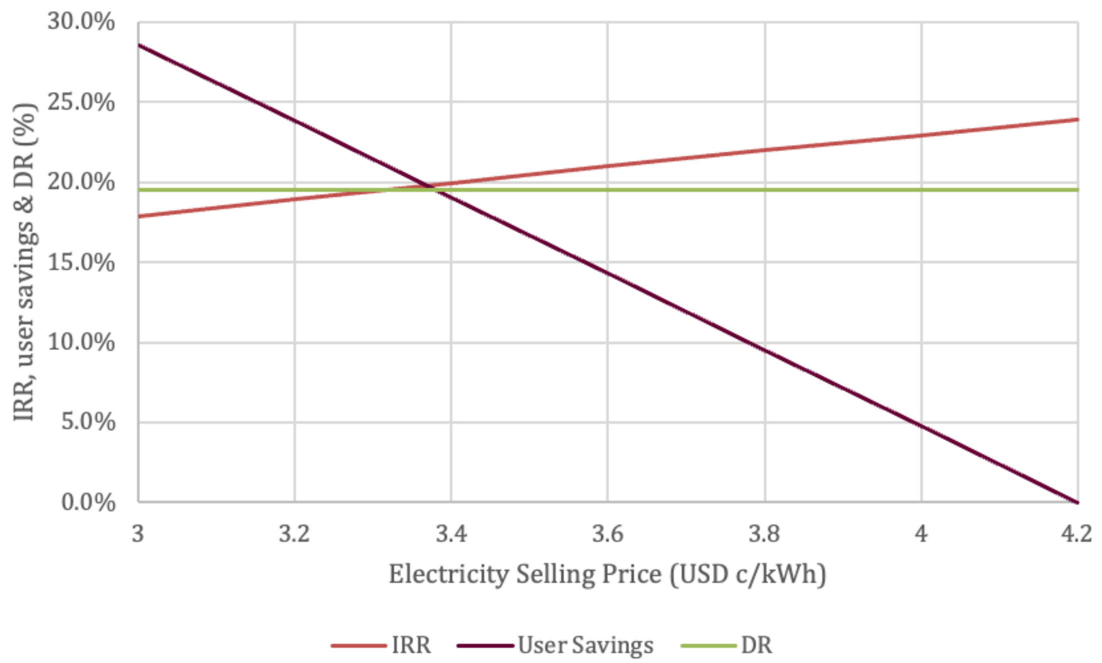

Figure 2. Impact of electricity selling price on IRR and user savings "Profile A"

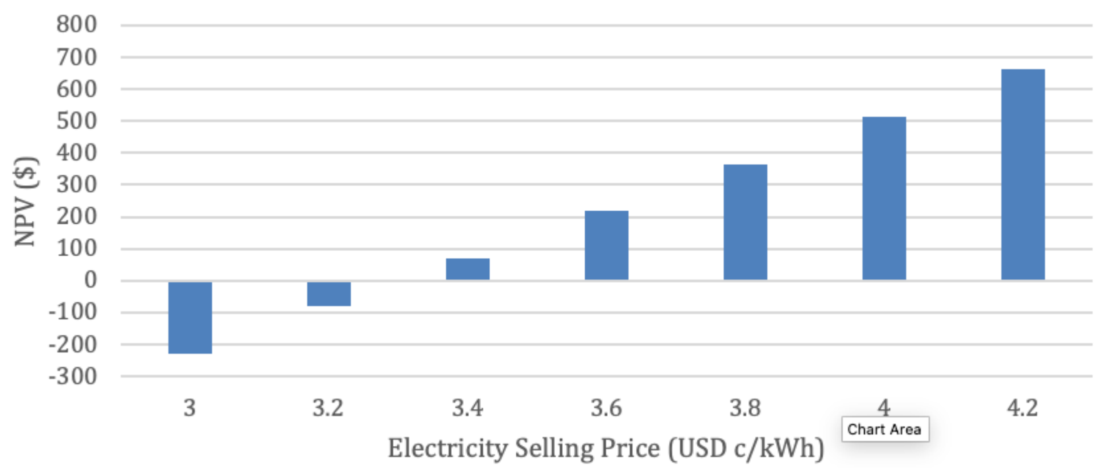

Figure 3. Impact of electricity selling price on NPV "Profile A"

The results indicate that reducing the PPA selling price has opposite effects on investor profitability and customer benefits. As the selling price decreases, customer savings increase; however, project profitability declines due to reduced revenue from electricity sales.

At the base-case tariff of 4.2 c/kWh, the project achieves an NPV of USD 661.7 and an IRR of 23.89%, indicating strong financial viability from the perspective of the TPO investor. As the selling price is progressively reduced, both NPV and IRR decline. Nevertheless, the project remains financially feasible until the selling price reaches approximately 3.4 c/kWh, at which point the project still generates a positive NPV of USD 69.3 and an IRR of 19.98%, slightly exceeding the discount rate of 19.5%.

This result suggests that the PPA provider could offer electricity at approximately 3.4 c/kWh while maintaining acceptable investment performance. Relative to the applicable grid tariff of 4.2 c/kWh, this corresponds to customer savings of approximately 19.1%. Further reductions in the PPA selling price result in a loss of project viability. At 3.2 c/kWh, the NPV becomes negative, and the IRR falls below the discount rate, indicating that the project no longer satisfies the selected investment criteria. Therefore, 3.4 c/kWh may be considered the practical lower limit for the PPA selling price under the assumptions adopted in this study.

These findings demonstrate that high-consumption households provide sufficient revenue generation to support both investor profitability and meaningful customer savings.

4.3.4. Sensitivity analysis of PPA selling price for high-consumption profile B

A sensitivity analysis was conducted to assess the effect of varying the PPA selling price on investor profitability and customer savings for High Consumption Profile B. The selling price was progressively reduced below the applicable grid tariff of 4.46 c/kWh, and the resulting changes in NPV, IRR, and customer savings were evaluated. The results are presented in Figures 4 and 5.

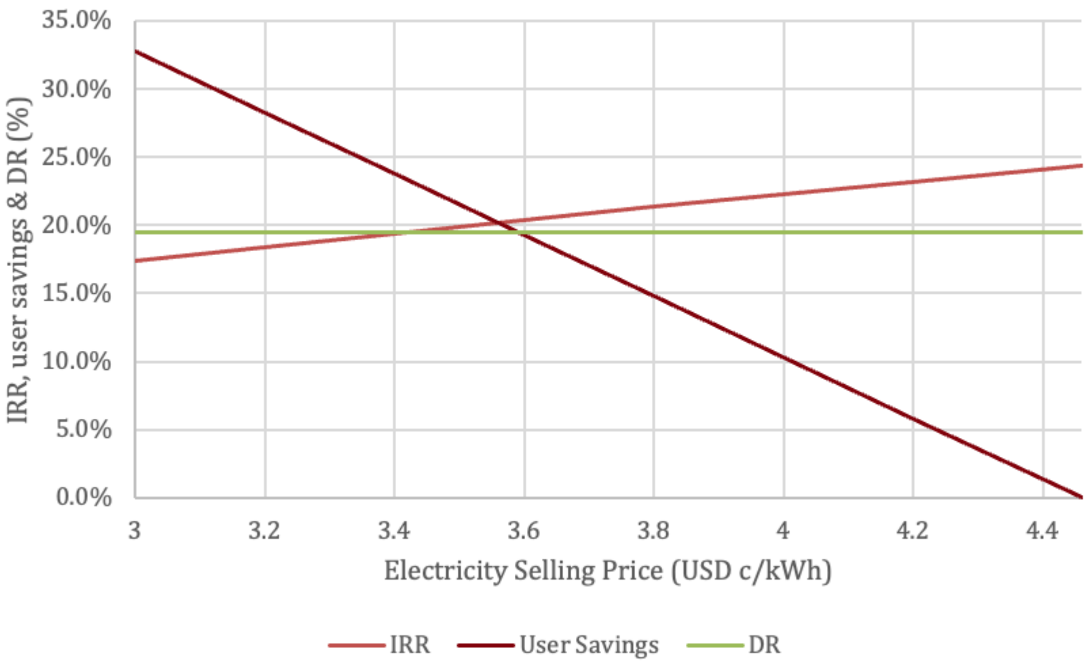

Figure 4. Impact of electricity selling price on IRR and user savings "Profile B"

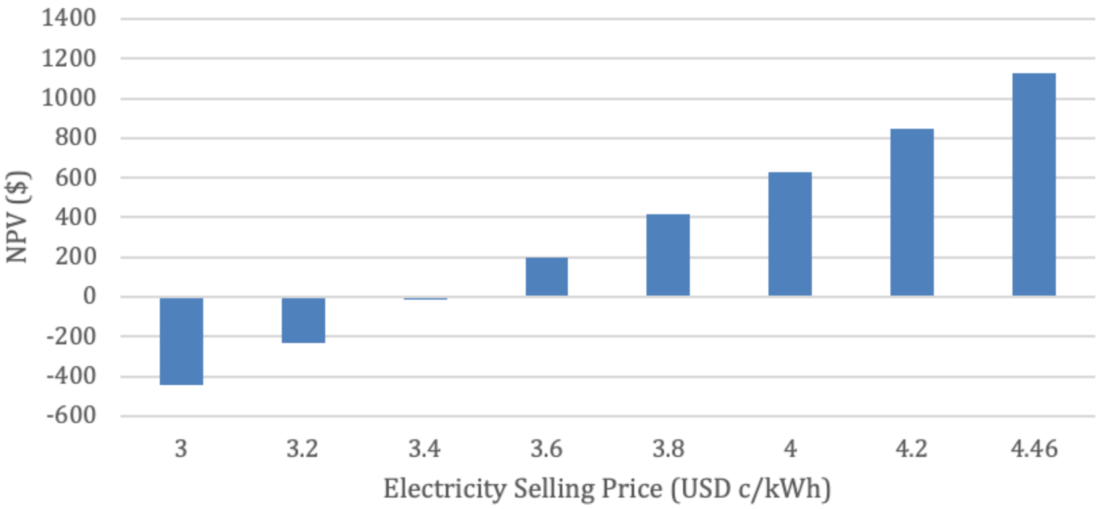

Figure 5. Impact of electricity selling price on NPV "Profile B"

The results indicate that project profitability decreases as the PPA selling price is reduced, while customer savings increase correspondingly. This trend is consistent with the findings obtained for High Consumption Profile A and reflects the inherent trade-off between investor returns and customer benefits within the PPA business model. At the applicable grid tariff of 4.46 c/kWh, the project achieves an NPV of USD 1,124 and an IRR of 24.3%, representing the strongest financial performance among the analysed consumption profiles. The high profitability can be attributed to the larger system capacity and the higher electricity tariff applicable to this customer category, both of which increase project revenues over the 25-year lifetime. As the selling price decreases, both NPV and IRR decline steadily. Nevertheless, the project remains financially feasible at a selling price of 3.6 c/kWh, with an NPV of USD 199 and an IRR of 20.4%, exceeding the 19.5% discount rate. At this price level, customers benefit from electricity cost savings of approximately 19.3% relative to the prevailing grid tariff. A further reduction in the selling price to 3.4 c/kWh results in a slightly negative NPV and an IRR below the discount rate, indicating that the project no longer satisfies the selected investment criteria. Consequently, the break-even selling price lies slightly above 3.4 c/kWh, representing the minimum tariff at which the project remains financially attractive to the TPO investor.

The results demonstrate that High Consumption Profile B can simultaneously provide meaningful customer savings and attractive investor returns. However, despite its superior profitability at the base tariff, the maximum achievable customer savings while maintaining project feasibility are comparable to those observed for High Consumption Profile A. This suggests that the primary advantage of serving very high-consumption households lies in enhanced investor profitability.

4.4. Discussion

The sensitivity analyses for the three residential consumption profiles show that the financial viability of the PPA model is heavily affected by both the electricity tariff and household consumption levels. Changes in the PPA selling price significantly impact project profitability and customer savings, underlining the trade-off between investor returns and consumer benefits. The results distinguish clearly between the medium-consumption profile and the two high-consumption profiles. For the medium-consumption household, a tariff of 2.92 c/kWh was insufficient to ensure a financially viable PPA project, resulting in a negative NPV and an IRR below the 19.5% discount rate.

The analysis suggests that the selling price would need to rise to about 3.40 c/kWh for the project to be feasible. Since this exceeds the current grid tariff, the PPA provider would have to charge customers more than the utility tariff, removing any potential savings for consumers and making the business less attractive. Conversely, both high-consumption profiles performed well financially at their respective grid tariffs. High Consumption Profile A had an NPV of USD 662 and an IRR of 23.9%, while High Consumption Profile B had an NPV of USD 1,124 and an IRR of 24.3%. These outcomes show that higher-consumption households can generate enough revenue to support attractive returns. The sensitivity analysis also indicated that both high-consumption profiles can tolerate significant reductions in PPA selling price while remaining profitable. The break-even tariff for both was about 3.4 c/kWh, offering customer savings of approximately 19%. This suggests PPA providers can offer discounts beyond the current grid price without risking project viability. Notably, although High Consumption Profile B had much higher NPVs than Profile A at the base tariff, both profiles had similar pricing flexibility. The maximum customer savings consistent with project feasibility were close to 19% in both cases. Therefore, the main benefit of the higher-consumption profile is not larger customer savings but greater financial returns for investors.

Overall, the findings imply that residential PPA projects are most viable in higher-tariff customer segments. Medium-consumption households do not provide sufficient revenue for a viable PPA business, while high-consumption households can yield both positive investor returns and meaningful savings. This indicates that high-consumption residential clients are the most promising market for rooftop PV systems via PPA in Egypt.

5. Conclusion and recommendations

This study evaluated the potential of the TPO model, implemented via a PPA, to encourage residential rooftop PV adoption in Egypt within the existing electricity tariff system. A techno-economic analysis was conducted for three variations of typical residential electricity usage profiles, focusing on rooftop grid-connected PV systems with a 25-year lifespan. Economic assessment showed all systems had low LCOE values, between 1.22 and 1.28 US cents per kWh, highlighting that rooftop PV can generate electricity at significantly lower costs than current residential rates. The results also suggested that the PPA model's financial attractiveness highly depends on the consumption level; at the medium level, negative NPV and IRR values below the discount rate were obtained. This means the current tariff had to be increased to make medium-level PV consumption financially attractive, thereby eliminating consumer savings. Both high-consumption profiles had positive NPVs with IRRs exceeding the discount rate, indicating strong financial attractiveness. The PPA selling price could be decreased, and the projects would remain viable. This results in a consumer savings of around 19% as compared to the cost of grid electricity.

In summary, the study found that the PPA-based TPO business model provides a feasible framework to increase the uptake of residential rooftop PV among high-consumption households in Egypt. This segment can generate sufficient demand to deliver competitive returns to investors and significant economic value to consumers, helping mitigate the high initial costs of PV deployment, which is one of the key barriers.

5.1. Recommendations

Based on this study's findings, the following recommendations are proposed:

- Focus on high-consumption residential customers during the initial market deployment, as they present the greatest economic opportunity for PPA-based rooftop PV projects and offer a balanced benefit between investor profitability and customer savings.
- Create financing mechanisms that facilitate third-party ownership structures. Governments, financial institutions, and private investors should work to improve access to funding for solar developers, promoting broader adoption of PPA projects.
- Keep net-metering regulations stable. Ensuring long-term policy stability is crucial for reducing investment risks and boosting investor confidence in residential rooftop PV initiatives.
- Broaden future research to explore additional business models. Comparing solar leasing, community solar, and peer-to-peer energy trading can provide valuable insights into the most suitable deployment strategies for Egypt.
- Investigate non-financial factors impacting adoption. Future research should examine consumer acceptance, regulatory hurdles, funding constraints, and stakeholder perspectives to facilitate the practical deployment of rooftop PV solutions in Egypt.

These recommendations aim to guide policymakers, investors, and researchers in promoting rooftop PV adoption and advancing Egypt's renewable energy and energy transition goals.

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