Evaluation of a Grid-Connected Residential Hybrid PV-BESS Under Iran's Regulatory Framework (Tavanir & SATBA): Load Supply During Power Outages and Techno-Economic Performance

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ABSTRACT

Frequent grid load shedding during summer months in Iran has increased the demand for continuous electricity supply in households. This study presents a techno-economic evaluation of a residential hybrid Photovoltaic-Battery Energy Storage System (PV-BESS) operating under the Tavanir and SATBA regulatory frameworks. A case study was conducted on a typical single-phase subscriber utilizing a 3 kW PV array integrated with a 6 kW all-in-one hybrid system equipped with a 5 kWh battery. The economic assessment, based on the Net Present Value (NPV) method, calculates revenue from surplus energy sold to the grid, thereby excluding the energy self-consumed during outages. Results show payback periods of 10.18 and 12.58 years at discount rates of 25% and 30%, respectively. While these periods may appear lengthy, the load supply evaluation demonstrates that the system covers the average household consumption during 3-hour outages year-round, and even meets the entire average daily consumption in most months. Furthermore, in a worst-case scenario operating at maximum contracted demand, the PV-BESS can sustain power for up to 2 hours. Ultimately, SATBA's guaranteed power purchase program acts as a supportive financial mechanism, allowing users to gradually recover their capital investment while securing uninterrupted power availability.

Keywords: *Hybrid PV-BESS (Photovoltaic-Battery Energy Storage System), Net Present Value, Load shedding, Guaranteed electricity sales*

1. *INTRODUCTION*

The global transition toward sustainable energy systems has significantly accelerated the deployment of renewable energy sources (RES). Among these, solar photovoltaic (PV) systems have emerged as a leading technology due to their environmental benefits, scalability, and continuously declining equipment costs. However, the inherent intermittency of solar generation presents challenges for grid stability. To address this, the integration of Battery Energy Storage Systems (BESS) with PV arrays has become more important. Combining PV with BESS not only mitigates power fluctuations but also improves power quality and empowers consumers to manage their energy profiles proactively [1].

Globally, policymakers have implemented various incentive mechanisms to encourage the adoption of residential grid-connected PV-BESS systems. Leading countries in the renewable transition have utilized strategies ranging from Feed-in Tariffs (FiTs) to upfront capital subsidies specifically targeted at battery storage installations [2]. These international policies aim to decentralize energy production, alleviate peak demand on the main grid, and increase consumer self-sufficiency.

In Iran, the development of renewable energy infrastructure is a growing national priority. The country possesses exceptional solar energy potential, experiencing roughly 300 clear sunny days per year with high average daily solar irradiance, making it a highly suitable region for widespread PV deployment [3]. To capitalize on this potential and promote decentralized power generation, the Renewable Energy and Energy Efficiency Organization (SATBA) provides financial incentives through guaranteed electricity purchase agreements. This framework allows residential consumers to sell their generated solar power directly to the grid. However, the installation and integration of these hybrid PV-BESS systems must strictly adhere to the regulations established by the Iran Power Generation, Transmission and Distribution Management Company (Tavanir) [4].

Beyond the financial incentives of selling energy, a critical driver for residential PV-BESS adoption in Iran is improving power reliability. Due to load-shedding events, these systems offer a practical dual advantage. During normal grid operations, the system exports surplus energy to the utility for financial gain. Conversely, during grid failures, the system can island itself, utilizing BESS and PV array to supply continuous backup power to the residence, thereby mitigating the impact of power interruptions [5].

1.1 Literature review

A substantial body of literature has investigated the integration of PV and BESS in residential buildings, with a primary focus on local load supply and energy sales to the grid [6-19].Ref [6] examined the economic viability of residential PV systems under different feed-in tariff and net metering schemes across sixteen geographic zones in Iran using a comprehensive economic analysis model. The results indicated that combining FIT with net metering was not beneficial under the prevailing tariff structure, but higher electricity prices could significantly improve PV investment returns. In [7], a study in the Netherlands assessed the financial potential of residential battery storage for PV-equipped households under dynamic day-ahead electricity pricing using linear programming with data from 225 homes. The analysis found that a 5 kWh battery yielded a maximum annual benefit of only €190 under net metering, and the proposed phase-out of net metering would further reduce profitability. Ref [8] evaluated behind-the-meter PV-battery business models in Brazil under net-metering regulations. Using a techno-economic analysis with TOU tariffs, the study found that PV-battery systems could be economically viable in locations with high solar radiation and large TOU differentials, although payback periods vary case by case. In [9], four energy policy scenarios for residential PV systems (net metering, net billing, zero-export with battery, and sell-all-buy-all) were evaluated for Jordan through detailed techno-economic modeling. Net metering and net billing offered the highest cost savings with ~3-year payback periods, while zero-export with battery increased self-sufficiency to 70% but required higher initial investment. Ref [10] proposed a real-time battery control strategy for smart homes with PV and battery systems. The strategy uses state-of-charge and demand-based algorithms to enable power arbitrage under variable electricity rates. Homes can buy power at low prices and sell or self-consume at high prices, benefiting all house types in a transactive distribution network. In [11], an economic analysis based on net present value (NPV) was conducted for integrated PV-battery systems in Italy under different policy contexts. The study found NPV values for a standalone PV system (without battery) ranging from 1,061 to 7,426 €/kW, and determined that battery affordability required a 14–35% increase in self-consumption along with tax subsidies above 50%. Ref [12] developed an optimal design model for residential PV storage systems in Spain. The model used real market prices, hourly smart meter data, and location-specific parameters under the country's simplified monthly billing scheme. The results demonstrated that self-consumption with battery storage improved economic returns compared to PV-only configurations. Ref [13] optimized PV-battery sizing for grid-connected Australian houses under flat, TOU, and mutually-agreed energy sharing prices using hourly data. The results demonstrated that tariff structures and peer-to-peer sharing arrangements significantly influence the levelized cost and economic feasibility of residential PV-battery systems.Ref [14] calculated the economic benefit of a 12.8-kWp PV system in Sweden using six years of real consumption and generation data, considering spot market pricing and tax effects on exported energy. The simulation of AC-coupled battery operation revealed that adding a battery with 2025 investment prices did not pay off if used only for increasing self-consumption, even though the PV alone was profitable. In [15], a two-stage stochastic optimization framework was presented for behind-the-meter PV-battery operation. This framework combined a neural network with error analysis and used real smart meter data from a house in the Aran Islands, Ireland. The results showed that it effectively mitigated sudden PV output changes and minimized daily grid consumption alongside battery degradation. Ref [16] modeled four energy trading scenarios (peer-to-grid, peer-to-grid with battery, peer-to-peer, and peer-to-peer with battery) using one year of hourly data from a 10 kW solar *house in Geelong, Australia. A 10 kWh battery with peer-to-peer sharing earned an estimated 4,929 AUD over 20 years, while grid-only sales gave negative returns due to low feed-in tariffs and battery costs. A Dutch study [17] employed a multi-objective genetic algorithm to quantify the techno-economic impacts of four pricing policies on an integrated residential PV-battery system. The results indicated that while the Real-Time Pricing (RTP) scenario initially yielded higher levelised costs and longer payback periods, it also significantly enhanced the self-consumption rate. The study further concluded that subsidising battery systems could offset the initial economic disadvantages of RTP, making it a viable policy to balance grid technical requirements with consumer benefits. A study in Sweden [18] investigated the operation of a spot-price controlled battery in a multifamily residential building. Simulations showed a standalone solar PV system reduced annual costs by 2,900 SEK, but adding a battery decreased those savings to 500-2,400 SEK, suggesting batteries for arbitrage are not profitable in the studied setting. Ref [19] evaluated the effect of tariff incentives on the optimal operation of grid-connected residential PV-battery systems in Poland. Using LSTM neural networks to address uncertainty, the results indicated installing a PV system alone reduces the energy bill by 40% (from €475.53 to €287.18), while battery coupling would fundamentally change grid utilization patterns.*

1.2 Contribution of paper

Globally, numerous case studies have evaluated the technical and economic aspects of integrating residential photovoltaic and battery energy storage systems (PV-BESS). However, in Iran, the lack of a practical study investigating these systems—specifically based on the regulations of Tavanir and SATBA—acts as a significant barrier to the development of this sector. To bridge this literature gap, this paper presents a case study with the following main contributions:

1. ***Technical Requirements Assessment:*** *Investigating and clarifying the technical requirements and permissible grid-connection topologies for residential hybrid PV systems intended for energy sales to the grid, strictly aligned with the latest standards of Tavanir and SATBA.*
2. ***Economic Evaluation:*** *Conducting an economic analysis utilizing the NPV model to provide a transparent financial outlook for prospective residential investors in Iran.*
3. ***Load Supply Assessment During power Outages:*** *Quantifying the system's capability to supply the household load during typical and worst-case outage scenarios, thereby evaluating its effectiveness as a reliable backup power source.*

1.3 *Paper's structure*

The remainder of this study is organized as follows. Section 2 examines the grid-connection requirements for hybrid PV systems intended for energy sales to the grid, based on Tavanir standards. The SATBA regulations for the guaranteed purchase of electricity from non-governmental renewable power plants are reviewed in Section 3. The load supply analysis during load shedding alongside the financial evaluation NPV for a specific case study is presented in Section 4, and finally, the paper is concluded in Section 5.

2. *Tavanir Regulations for Grid-Connecting Hybrid PV Systems for Energy Sales*

According to Tavanir regulations, customers intending to connect a hybrid PV system to the grid for energy sales are required to install a dedicated export meter to measure the injected energy. This is in addition to the standard demand meter used to measure the energy imported from the grid. Tavanir has defined four approved configurations (topologies) for hybrid PV systems, which are discussed below.

2.1. Hybrid PV Systems with Battery Storage

The architecture of the hybrid PV system with battery storage is illustrated in Fig. 1.

Power Source Connection: *Both the PV modules and the battery are directly connected to a single hybrid inverter.*

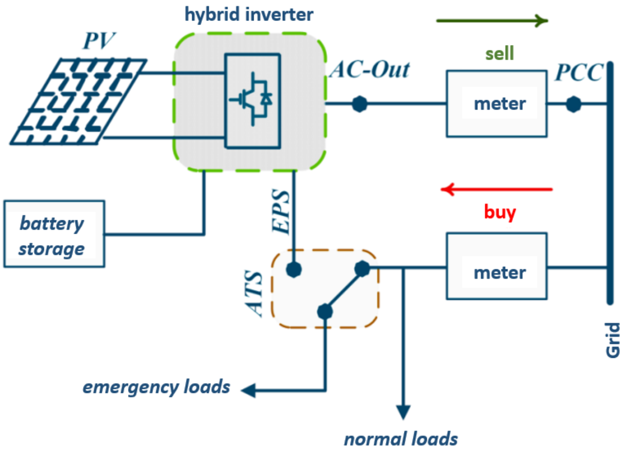

Fig. 1. *The architecture of the hybrid PV system with battery storage*

Islanded Mode Operation: *In the event of a load shedding, the main output switch of the inverter disconnects. Subsequently, an Automatic Transfer Switch (ATS) transfers the emergency loads—which were previously supplied by the grid via the demand meter—to the inverter's Emergency Power Supply (EPS) port. These loads are then seamlessly powered by the PV system and the battery.*

2.2. Hybrid Systems with Battery and Diesel Generator

When both a hybrid inverter and a diesel generator are utilized, the following configurations can be defined:

2.2.1 Direct Connection of the Diesel Generator to the Hybrid Inverter

The architecture of direct connection of the diesel generator to the hybrid inverter is illustrated in Fig. 2.

Power Source Connection: *The PV modules, battery, and diesel generator are all directly connected to the hybrid inverter.*

Islanded Mode Operation: *Following a load shedding, the diesel generator starts automatically via a start command received from the hybrid inverter. The emergency loads (connected to the inverter's EPS port) are then supplied collectively by the PV, diesel generator, and battery.*

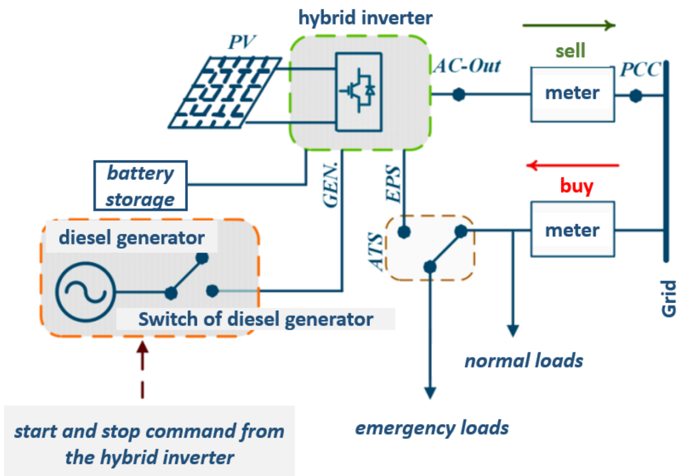

Fig. 2. *The architecture of direct connection of the diesel generator to the hybrid inverter*

2.2.2 Parallel Operation of the Diesel Generator and Hybrid Inverter

The architecture of parallel operation of the diesel generator and hybrid inverter is illustrated in Fig. 3.

Power Source Connection: *The PV and battery are connected to the hybrid inverter. The diesel generator and the hybrid inverter are paralleled externally through an ATS panel.*

Islanded Mode Operation: *In the event of a load shedding, the emergency loads connected to the inverter's EPS port are supplied by the PV and battery. The emergency loads connected to the common output (AC-out) of the hybrid inverter and the diesel generator are supplied by the PV, diesel generator, and battery.*

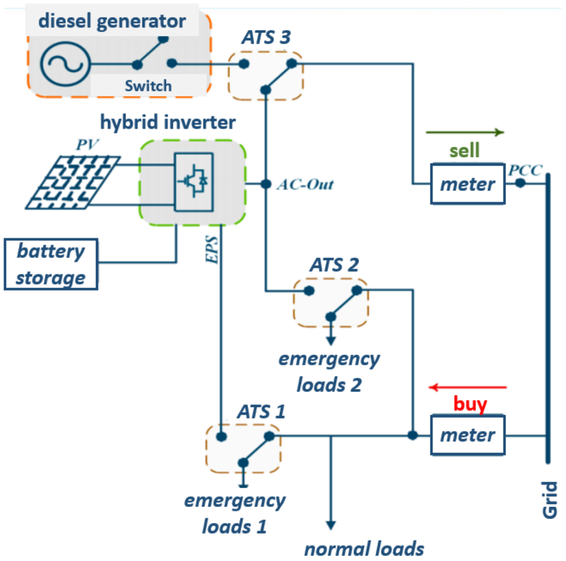

Fig. 3. *The architecture of parallel operation of the diesel generator and hybrid inverter*

2.2.3 Two Separate Networks (Independent operation of the diesel generator and the hybrid inverter)

The architecture of Independent operation of the diesel generator and the hybrid inverter is illustrated in Fig. 4.

Power Source Connection: *The PV and battery are connected to the hybrid inverter, while the diesel generator is independently connected to its own dedicated emergency loads.*

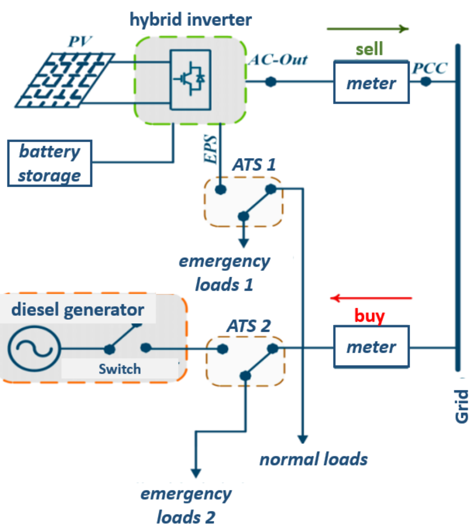

Fig. 4. *The architecture of Independent operation of the diesel generator and the hybrid inverter*

Islanded Mode Operation: *In the event of a load shedding, the emergency loads connected to the inverter's EPS port are supplied by the PV and battery. The emergency loads connected to the output of the diesel generator are supplied exclusively by it.*

2.3. System with Parallel Hybrid Inverters

The architecture for paralleling multiple hybrid inverters is illustrated in Fig. 5.

Power Source Connection: *Each hybrid inverter is connected to its own dedicated PV and battery system. Note: A diesel generator can be integrated into this architecture following the three methods described previously: direct connection, parallel operation, or as a separate network.*

Islanded Mode Operation: *Following a load shedding, the entire emergency load is connected to the common EPS output of the paralleled inverters. In this mode, the load is supplied by the combined power from the PVs and batteries associated with each inverter.*

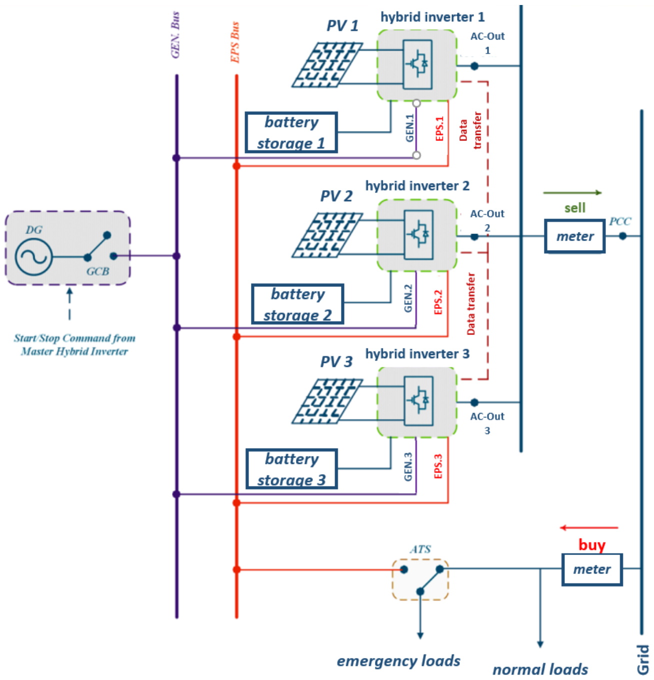

Fig. 5. *The architecture for paralleling multiple hybrid inverters*

2.4. Connection of an on-grid PV Inverter to a Hybrid Inverter (AC Coupling)

The architecture for Connection of an on-grid PV Inverter to a Hybrid Inverter is illustrated in Fig. 6.

Power Source Connection: *The PV modules, battery, and on-grid inverter are all directly connected to the hybrid inverter.*

Islanded Mode Operation: *Following a load shedding, the emergency loads connected to the inverter's EPS port are supplied collectively by the PV, on-grid inverter, and battery.*

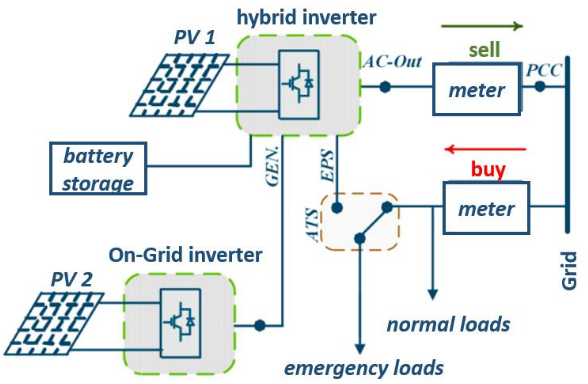

Fig. 6. *The architecture for Connection of an on-grid PV Inverter to a Hybrid Inverter*

The following operational constraints are mandated for all the aforementioned architectures:

- *During grid-connected operation, the hybrid inverter is prohibited from charging the energy storage system from the grid or discharging it back into the grid.*
- *In grid-connected mode, the hybrid PV system is permitted only for two functions: charging the energy storage system (using PV power) and injecting PV power into the grid for sale. Consequently, supplying the local residential loads from the system is prohibited.*
- *The diesel generator is permitted to operate only during a grid outage.*
- *Alternatively, the ATS for the hybrid inverter(s) can be omitted. In this configuration, the emergency load is wired directly to the inverter's EPS output. Consequently, this load is permanently powered by the inverter and is strictly prohibited from being connected to the grid.*

3. SATBA regulations for the guaranteed purchase of electricity from non-governmental solar power plants

The SATBA directive for the guaranteed purchase of electricity from non-governmental solar power plants with a capacity of up to 200 kW is outlined as follows:

A) The sale of energy to SATBA is conditional upon full compliance with the grid-connection requirements for hybrid photovoltaic systems, as stipulated by Tavanir.

B) The minimum capacity for the battery energy storage system integrated with the solar plant is specified as 1.5 kWh per kilowatt of installed PV panel capacity.

C) To compensate for economic fluctuations, the electricity purchase rate is regularly updated through an adjustment factor based on changes in the consumer price index and currency exchange rates. Furthermore, at the beginning of the 8th, 12th, and 16th years of operation, the final invoiced amount is subject to a rate reduction factor (also known as the period factor) of %60.

4. Load supply analysis during load shedding alongside the financial evaluation NPV for a specific case study

Due to significant load shedding caused by energy imbalances in Iran, and considering SATBA's regulations—which dictate that in grid-connected mode, the PV system can only charge the battery and sell energy to the grid, without supplying local loads—most users prefer to utilize PV-BESS for backup power during outages while selling the surplus energy. Accordingly, this section presents a load supply and economic analysis (using the NPV method) for a residential user with a single-phase 25 A meter, using a 3 kW PV system paired with an integrated hybrid BESS.

For this case study, both single-phase and three-phase integrated hybrid systems from Mapna Group were considered, as they fully comply with Tavanir's grid-connection standards and support backup mode operations. The single-phase model was ultimately selected to align with the residential user's existing grid infrastructure. This 6 kW all-in-one hybrid system is available with multiple battery capacities (e.g., 5, 10, and 15 kWh); the model equipped with a 5 kWh battery was chosen for this analysis to strike an optimal balance *between the initial investment cost and the energy autonomy required to cover the household's typical consumption during load shedding periods. The technical specifications of the selected system are detailed in Table 1, and an overall view of the product is illustrated in Fig. 7. Furthermore, according to the 2026 SATBA directive, the base guaranteed purchase rate for non-governmental solar power plants up to 200 kW is set at 91,169 IRR/kWh. The annual adjustment factor for the purchase rate is assumed to be approximately 38%, based on a 10-year weighted average. The details of initial investment costs (equipment procurement and installation) are provided in Table 2. Also, using the meteorological data for Mashhad, the hourly power generation of the 3 kW PV system was simulated via PVsyst software. The corresponding monthly energy generation is depicted in Fig. 8. To model realistic grid conditions during peak summer demand (12:00 to 17:00), load shedding is assumed to occur daily from 13:00 to 16:00 from May 22 to September 22 (Khordad to Sharivar), and one day per month during the same hours for the rest of the year. Since the system supplies emergency local loads during these outages, both the PV generation within these hours and the energy stored in the battery required for backup operation are excluded from the total energy sold to the grid in the financial calculations.*

Table 1*. Technical specifications of Mapna Group's 6 kW all-in-one hybrid system with a 5 kWh battery*

Efficiency	Maximum charging power (kW)	Maximum discharging power (kW)	Battery Capacity (kWh)	Depth of Discharge (DOD)
97.8%	5	6	5	Max 100% (Adjustable)

Fig. 7. The *overall view of Mapna Group's 6 kW all-in-one hybrid system with a 5 kWh battery*

Table 2*. The details of initial investment costs (equipment procurement and installation)*

3 kW PV system (IRR)	The 6 kW all-in-one hybrid system with a 5 kWh battery (IRR)
1,500,000,000	3,990,000,000

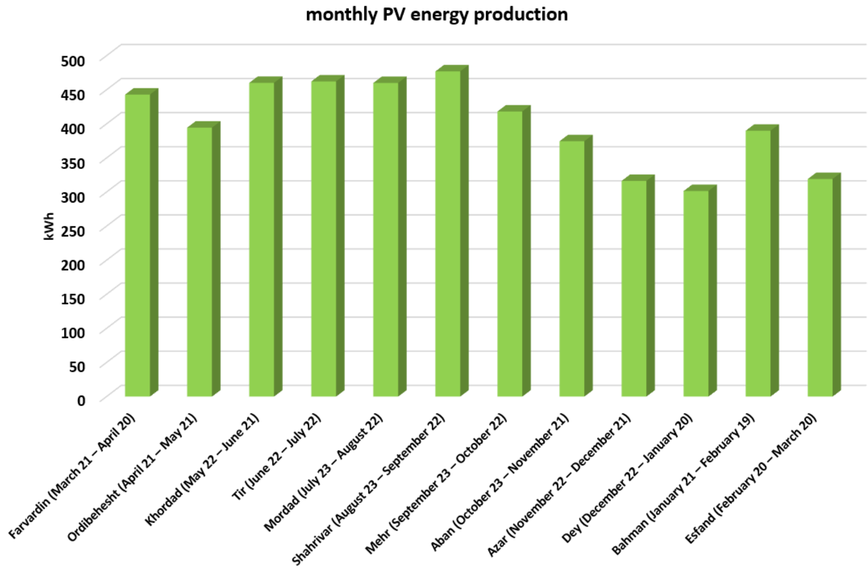

Fig. 8. *The monthly PV energy generation*

4.1. Economic Analysis

The economic viability of the proposed PV-BESS system is evaluated using the NPV method, which determines the profitability of an investment by calculating the difference between the present value of cash inflows and outflows over a specific period. A project lifetime of 20 years is considered for this analysis, aligning with SATBA's long-term guaranteed power purchase agreements for renewable energy systems in Iran. To account for financial uncertainties and assess the investment's sensitivity to market fluctuations, the analysis is conducted under two distinct scenarios with different discount rates: a baseline scenario with a 25% discount rate and a more conservative scenario with a 30% discount rate.The NPV is calculated using the Equation (1), [20].

$$NPV = \sum_{t=0}^{N} \frac{CF_t}{(1+r)^t} \tag{1}$$

Where CF_t , r, N, and t are the net cash flow during period t, the discount rate, the total number of periods (20 years), and the time period (year), respectively.

The payback period, representing the time required to recover the initial capital investment, is determined for both scenarios and presented in Table 3. Furthermore, the annual discounted cash flow and the cumulative NPV for the 20-year horizon are illustrated in Fig. 9. In this figure, the payback period is identified as the year in which the cumulative NPV curve intersects the horizontal axis, indicating that the initial investment has been fully recovered.

***Table 3**. Payback periods for discount rates of 25% and 30%*

Discount rate	Payback period
25%	10.18
30%	12.58

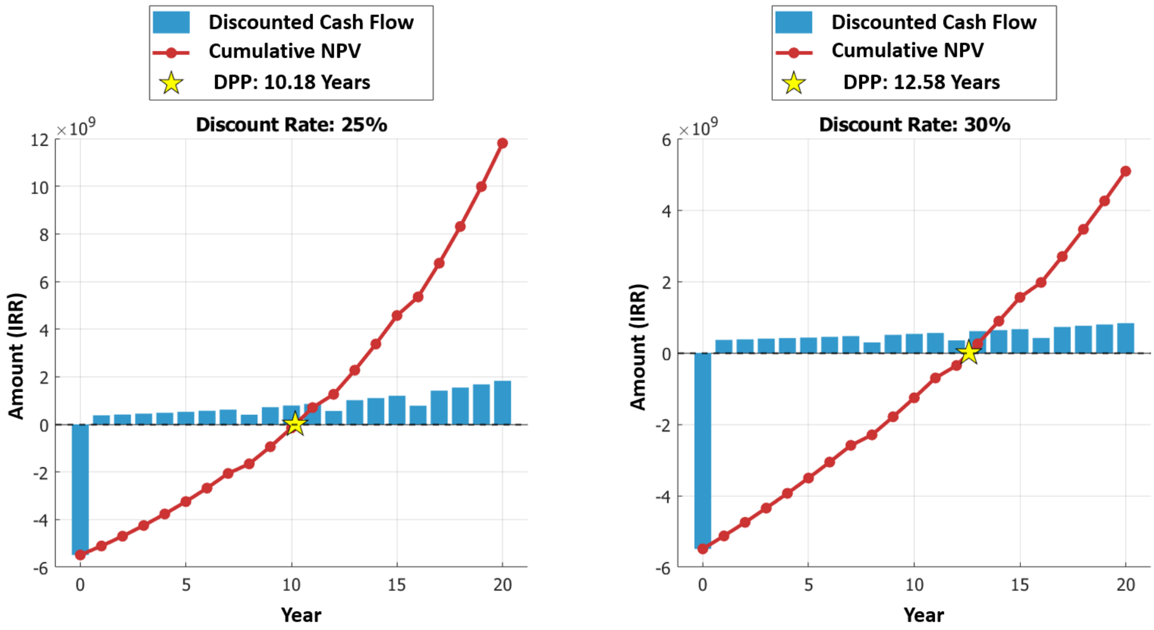

Fig. 9. *The annual discounted cash flow and the cumulative NPV for the 20-year horizon*

As expected, the payback period increases with a higher discount rate, reaching 10.18 and 12.58 years for the 25% and 30% scenarios, respectively. To further encourage residential investments and help shorten this timeframe, it is suggested that SATBA consider a proportional increase in the guaranteed purchase tariffs.

4.2. Load Supply Analysis During Load Shedding Period

To evaluate the system's performance during the load shedding period, the household's electricity bills for the year 2025-2026 were analyzed. Based on the billing data, battery capacity, and the PV power, the load supply capability during the scheduled load shedding hours (13:00 to 16:00) was calculated. The results are summarized in Table 4. According to the results, the integrated PV-ESS system can successfully supply 100%

***Table 4**. Load supply capability of the PV-BESS system*

Electricity Billing Cycle	Average Energy Consumption During Load Shedding (13:00-16:00) (kWh)	Average Daily Energy Consumption (kWh)	PV+BESS Energy Available During Load Shedding (13:00-16:00) (kWh)
2025-03-21 to 2025-04-05	0.53	4.57	5.85
2025-04-05 to 2025-06-09	0.57	3.26	6.98
2025-06-09 to 2025-08-06	1.08	10.43	8.40
2025-08-06 to 2025-10-02	0.79	7.09	8.33
2025-10-02 to 2025-12-03	0.59	5.34	5.95
2025-12-03 to 2026-02-10	0.60	5.64	6.24
2026-02-10 to 2026-03-20	0.67	4.90	8.32

of the household's average energy demand during the load shedding hours. Furthermore, the system is capable of covering the entire average daily energy consumption across almost all billing cycles. The only exception is the peak summer period (from mid-June to early August), where it covers approximately 81% of the average daily consumption. Additionally, a worst-case scenario was analyzed assuming the user draws their maximum contracted demand of 5 kW (based on the studied subscriber's meter capacity) during summer load shedding. Under this maximum-load condition, the system can still provide backup power for approximately 2 hours.

While the calculated payback periods may initially appear lengthy, the system's practical benefits and its ability to ensure reliable power during grid outages provide favorable added value. The system significantly improves user comfort by maintaining power for essential loads during grid load shedding. In this context, SATBA's guaranteed power purchase program provides a valuable financial mechanism. It allows users who primarily install these hybrid systems for backup reliability, to gradually recover their capital investment alongside securing a reliable power supply.

5. *Conclusions*

Since compliance with Tavanir's grid-connection rules is a mandatory requirement for participating in SATBA's guaranteed electricity purchase program, this paper investigated the permitted grid-connection topologies for residential hybrid photovoltaic systems. Accordingly, four permitted configurations were identified. In all these topologies, charging the battery from the grid and discharging it back to the grid are strictly prohibited. Furthermore, in grid-connected mode, the PV system is only allowed to charge the battery and export power to the grid, without directly supplying local loads. Based on these regulatory constraints, two main analyses were conducted: an economic assessment for the grid-connected mode, and a load-supply evaluation during load shedding. The case study considered a residential user equipped with a single-phase 25 A meter. To meet the requirements of this user, a system consisting of a 3 kW PV array and a 6 kW all-in-one hybrid system equipped with a 5 kWh battery was selected.

The economic analysis was performed using the NPV method, based on SATBA's guaranteed purchase tariffs. Considering the initial investment costs of the selected hybrid PV-BESS, the payback periods under discount rates of 25% and 30% were calculated at 10.18 and 12.58 years, respectively.

The load-supply analysis evaluated the system's performance during 3-hour load shedding periods across various months. The results demonstrated that the system can fully cover the average energy consumption during load shedding hours in all months. In most months, it can even supply the entire daily average energy consumption. In a worst-case summer scenario, where the household draws power up to the meter's maximum demand of approximately 5 kW during an outage, the system can provide backup power for about 2 hours.

Due to frequent load shedding in Iran, the primary motivation for residential users to install hybrid PV-BESS is often to prevent power interruptions. These systems are highly useful because they provide reliable electricity when the grid fails. At the same time, selling the generated energy to the grid through SATBA's guaranteed purchase program helps users recover their investment costs over time.

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