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IMPROVEMENT OF METHODS FOR INCREASING THE ENERGY EFFICIENCY INDICATORS OF AN OFF-GRID SOLAR PHOTOVOLTAIC SYSTEM

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Abstract: Globally, renewable energy sources are increasingly being utilized to supply consumers with reliable, high-quality, and continuous electrical power. In our country, special attention is given to ensuring uninterrupted electricity delivery and improving energy efficiency by developing solar photovoltaic systems that are well suited to the local climatic conditions. In addition, the effective planning and optimization of operating modes of existing energy systems are examined through an assessment of consumer requirements and established recommendations.This study investigates the optimal sizing of solar photovoltaic (PV) systems and battery energy storage (BES) units for a single configuration using a newly developed rule-based energy management strategy. Two system layouts are considered: (i) a PV-only system and (ii) a combined PV-BES system. The performance optimization of a grid-connected residential household is evaluated using one year of realistic operational data. Furthermore, uncertainty analysis is conducted by accounting for variations in solar irradiance, ambient temperature, and electrical load. Sensitivity analyses are performed with respect to average daily demand, grid limitations, and the cost parameters of PV and BES technologies.

Keywords: renewable energy, electrical power, photovoltaic systems, ToU–Flat, battery, power supply scheme, PV–BES systems, High-quality photovoltaic.

Introduction. The global transition toward renewable energy sources has significantly expanded in recent years, driven by the need to supply consumers with reliable, high-quality, and continuous electrical power. In a similar manner, our republic has actively promoted the generation of electricity from renewable sources—such as solar, wind, and small-scale hydropower—over the past five years, in line with presidential directives. These energy sources are recognized as environmentally sustainable, economically viable, and well adapted to the climatic conditions of Central Asia, while also being free from carbon emissions [1]. In this context, several presidential resolutions and decrees have been adopted to support the development of modern power grids and electrical systems integrated with centralized industrial electricity networks. In particular, the Resolution of the President of the Republic of Uzbekistan dated March 27, 2019 (No. PQ-4249), implemented within the framework of the New Uzbekistan Development Strategy for 2022–2026, outlines key measures for the transition to a “Green Economy” and the enhancement of energy efficiency, with the objective of reducing losses in industrial sectors and improving the effectiveness of resource utilization.

The cost of solar photovoltaic (PV) modules has experienced a substantial decline of up to 28% since 2019 [2]. Alongside these cost reductions, international commitments to carbon neutrality have further accelerated the global deployment of solar PV technologies. Nevertheless, despite their environmental advantages, solar PV systems inherently suffer from a mismatch between electricity generation and household consumption patterns [2]. This mismatch, caused by the intermittent nature of renewable energy sources, highlights the necessity of integrating PV systems with electrical grids or battery energy storage (BES) systems. Recent analyses indicate that, particularly in valley regions, the balance between installed solar PV capacity and battery storage capacity remains inadequate. In most cases, newly deployed battery systems represent less than 10% of the total installed PV capacity [3]. Although batteries are widely recognized for their capability to mitigate peak household demand and reduce electricity costs during high-tariff periods, their economic benefits remain constrained by high investment costs, necessitating further investigation. Moreover, the installed capacity of solar PV systems directly influences power exchange among different energy sources and significantly affects the total system cost [5]. Consequently, determining the optimal capacities of PV and BES systems is essential for minimizing overall system expenditures.

In conventional industrial power grids, electricity tariffs during peak alternating current demand periods play a crucial role in shaping grid import and export prices, thereby influencing the economic performance of integrated energy systems [6]. For instance, consumers connected to traditional grid structures often benefit from lower electricity prices during off-peak or low-voltage periods. Historically, optimal PV sizing has predominantly been analyzed under a single electricity price assumption, which underscores the need to extend such evaluations to multiple tariff structures. Effective management of energy flows among solar PV systems, battery storage units, and industrial grid schemes can substantially reduce electricity payment costs.

Numerous studies have addressed the optimization of PV and battery storage capacities. In [7], a grid-connected solar-based system was designed to minimize total life-cycle costs while maintaining reliability, demonstrating that optimal PV sizing can reduce electricity expenses by up to 44% compared to systems without solar integration. However, battery energy storage was not considered in that analysis. Other studies [8,9] focused on optimizing battery capacity to reduce system costs under fixed electricity price conditions, revealing that battery cost is a critical factor affecting economic performance. Nevertheless, these studies did not include the simultaneous optimization of solar PV capacity.

Furthermore, several investigations have explored system operation under various electricity tariff schemes, including flat-rate tariffs, conventional industrial grid tariffs, and real-time pricing (RTP) mechanisms. Despite these efforts, the proposed energy management systems (EMSs) were predominantly based on net metering strategies. Net metering represents a basic EMS approach, wherein excess PV-generated electricity is exported to the grid after meeting local demand and charging the battery, without accounting for fluctuations in electricity prices.

To obtain realistic and practically applicable results in determining the optimal capacities of PV and BES systems, it is essential to incorporate all relevant technical and economic factors. These include photovoltaic and battery degradation, residual or salvage value at the end of the project lifetime, real operational data, and applicable electricity tariffs. However, a large number of existing studies on PV–BES capacity optimization neglect the degradation behavior of PV modules and batteries, which can result in inaccurate long-term economic assessments.

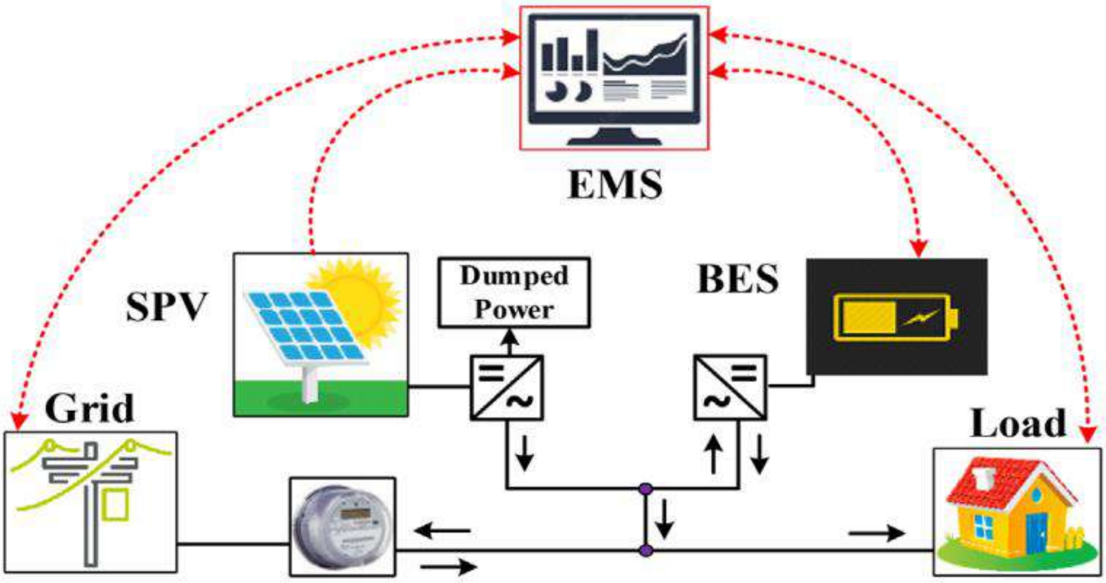

Figure 1. Off-grid–supplied consumer power supply scheme

In this configuration, a uniform electricity tariff is applied to both energy purchasing and selling, meaning that the electricity price remains constant over daily and annual operating periods. The energy management system (EMS) continuously receives information related to household load demand, renewable energy production, and grid operating constraints. When renewable generation exceeds residential electricity demand, the EMS prioritizes exporting surplus power to the industrial grid after the battery energy storage system has been fully charged.

Furthermore, investigations of renewable energy systems operating under multiple electricity tariff structures remain limited, as most simulation-based analyses are conducted using a single tariff scheme, such as flat-rate or Time-of-Use (ToU) pricing. Although optimal sizing of PV–BES systems has been explored under certain grid limitations, the effects of PV and battery degradation have often been omitted. In some improved approaches for grid-connected PV–BES systems, the optimal number of PV panels and batteries was determined; however, the maximum allowable export power from the PV system to the grid was not considered. Accounting for power exchange limits between consumers and the utility grid is critical to maintaining grid stability, particularly in scenarios with high penetration of solar PV installations. Despite this, several PV capacity optimization studies have been carried out without explicitly incorporating grid constraints. According to the configuration illustrated in Figure 1, any remaining surplus energy is exported to the grid once the battery storage system reaches full capacity.

Results: When the battery is fully charged, the remaining energy is sold to the grid. The charged power of the battery (Pcha,BES) and the power exported and sold to the grid (Pex,grid) are determined by the following formula:

Charged power of the battery (P_{cha} BES)

$$P_{BES}^{cha}(t) = min\,(P_{re}(t) - P_{leand}(t)$$

(BES) and the exported power to the grid (P_{ex})

$$P_{grid}^{ex}(t) = min\,(P_{re}(t) - P_{leand}(t) - P_{BES}^{cha}(t)$$

In this context, Pre represents the electrical power produced by the solar photovoltaic system, Pload denotes the household load demand, and Pmax refers to the maximum permissible power that can be exported to the grid. The term Pin,BESP indicates the available charging power of the battery energy storage system and is determined as a function of the battery state of charge (SOC), as expressed below:

$$P_{BES}^{in}(t) = min\,(P_{BES}(\frac{E_{BES} * (SCO^{max} - SCO(t))}{\Delta t}))$$

Now, the maximum power that can be discharged by the BES at each time interval is calculated as follows:

$$P_{BES}^{out}(t) = min\,(P_{BES}(\frac{E_{BES} * (SCO - SCO^{min}}{\Delta t}))$$

The state of charge (SOC) for charging and discharging the battery is calculated as follows:

$$SCO(t + \Delta t) = SCO(t) + \frac{P_{BES}^{Cha}(t) * \eta_{ch} - P_{BES}^{dis}(t) * \eta_{ch} * \Delta t}{E_{BES}}$$

On the basis of this formulation, the control algorithm designed to operate following the sequence illustrated in Figure 1 is depicted in Figure 2. This approach has been successfully employed in energy system planning research, and its effectiveness in achieving optimal system sizing has been verified through comparisons with alternative methods. It should be emphasized that the optimization algorithm itself was not explicitly implemented within the scope of this study. Among various optimization techniques, particle swarm optimization (PSO) offers several notable advantages, including its capability to efficiently address nonlinear system characteristics, its conceptual clarity, straightforward implementation, rapid convergence behavior, reduced sensitivity to initial conditions, and overall computational efficiency. This study focuses on evaluating the performance of solar photovoltaic systems under real operating conditions. The results indicate that the quality of solar panels is strongly influenced by manufacturing technology, temperature sensitivity, and long-term degradation characteristics. High-quality photovoltaic modules significantly reduce voltage and power losses during prolonged operation. Climatic factors, particularly elevated ambient temperatures and variations in solar irradiance, have a noticeable impact on system efficiency. Therefore, system design should consider not only the nominal power rating but also the reliability and quality of photovoltaic panels. This approach enhances energy generation stability and improves the overall economic performance of solar energy systems.These characteristics and the operational flow of the method are illustrated in Figure 2.

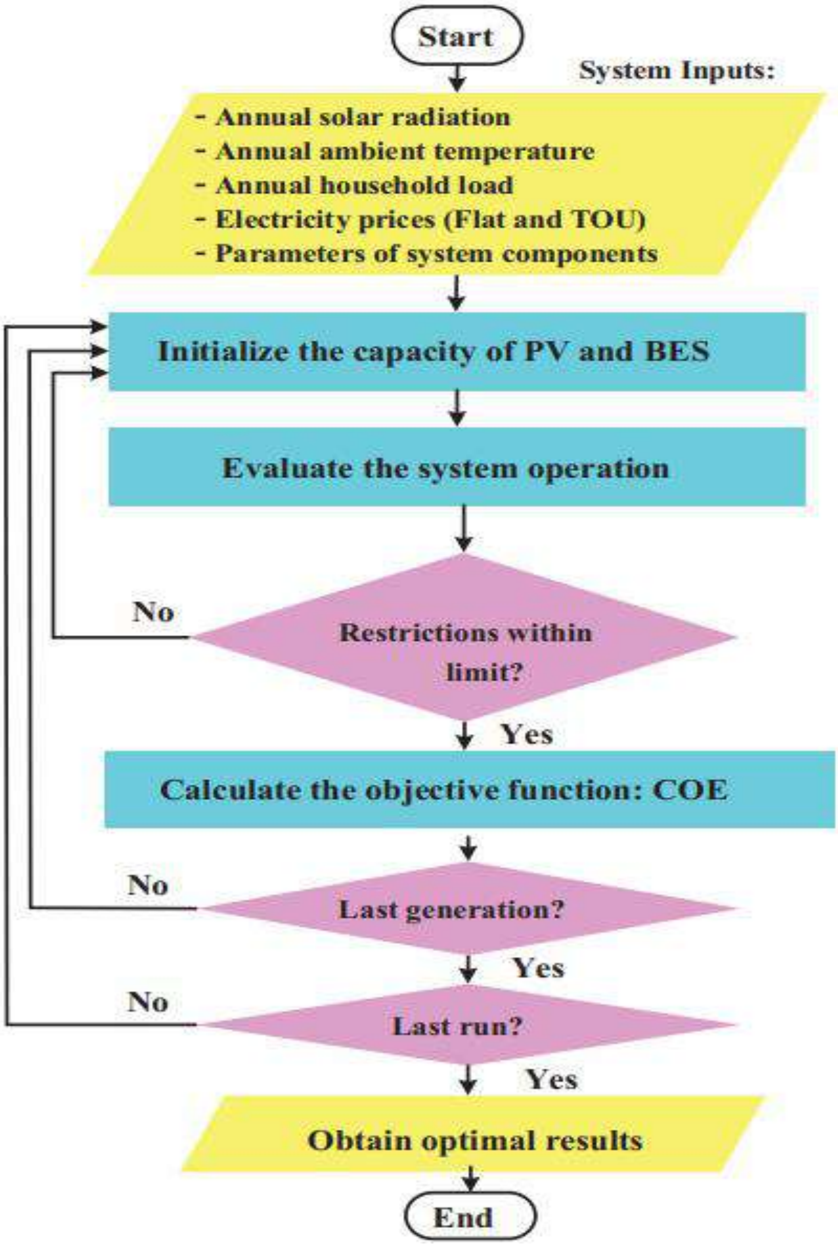

Figure 2. Algorithm developed to achieve efficiency by selling the electrical energy generated by a centralized solar photovoltaic system to the industrial power grid

As Uzbekistan, including its valley regions, is geographically situated in the eastern hemisphere along the sunrise direction, solar meteorological conditions are generally favorable during both sunrise and sunset periods, while lower solar potential is observed toward the end of the year. From a solar irradiance standpoint, higher levels of usable solar energy are available during the summer season due to extended daylight hours. The peak solar irradiance reaches 0.79 kWh/m^2, whereas the annual average value is approximately 0.18 kWh/m^2. The operating temperature of the photovoltaic modules varies significantly, with recorded maximum and minimum values of 45.9 °C and 2.2 °C, respectively. Furthermore, the average ambient temperatures during summer and winter are 37.4 °C and 7.9 °C, respectively. As a result of these temperature variations, the output voltage of the solar photovoltaic system changes accordingly, as illustrated in the graph below.

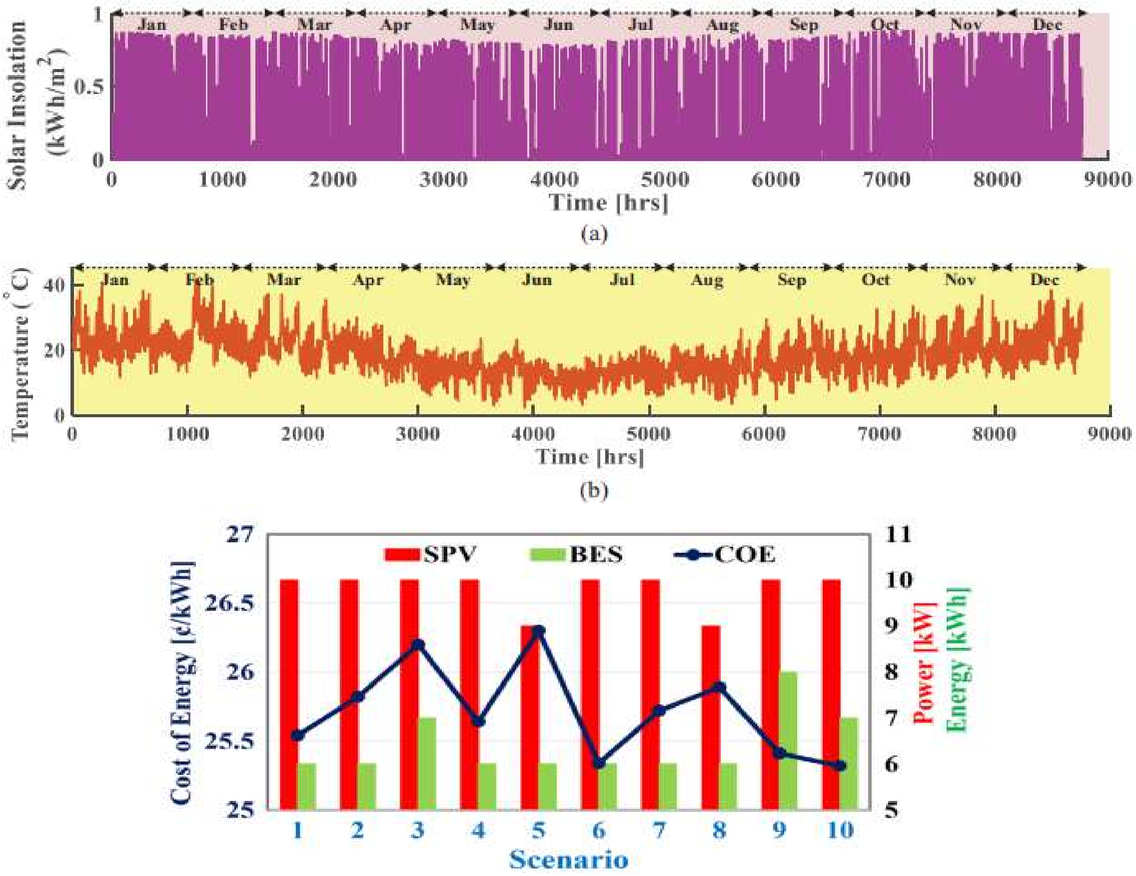

Figure 3. Time-dependent graph of the output voltage of the electrical energy generated by the solar photovoltaic system

Uncertainty analysis and conclusions: The uncertainty assessment demonstrates that a photovoltaic system rated at 10 kW, combined with a 6 kWh battery energy storage unit, offers sufficient robustness to accommodate variations in household electricity demand and solar irradiance. Comparative analysis between the proposed energy management strategies and the conventional net metering approach reveals that the newly introduced EMSs consistently achieve a lower cost of energy (COE) across all evaluated scenarios. Although a case study based on South Australian conditions was utilized to validate the proposed methodology, the developed approach is not location-specific and can be readily adapted to other geographical regions.

Conclusion: The principal contribution of this research is the optimal sizing of photovoltaic (PV) and battery energy storage (BES) systems through the implementation of newly developed rule-based energy management systems under both Time-of-Use (ToU) and Flat electricity tariff structures. The analysis was conducted for grid-connected and off-grid residential applications within two RP and FiT scheme combinations: (1) Flat–Flat and (2) ToU–Flat. Future extensions of this work may involve the incorporation of a real-time pricing (RTP) electricity framework. Due to its higher responsiveness to price fluctuations, RTP can broaden consumer participation models and facilitate the deployment of more efficient strategies for electricity purchasing and selling. Additionally, further research should focus on long-term, multi-year operational analysis that explicitly accounts for battery capacity degradation over time, as storage performance may gradually decline throughout the system lifespan.

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