

## Stochastic Scheduling of Integrated System of Solar Resources and Hydrogen Storage in the Smart Distribution Network Considering a Multi-Objective Energy Management Model

Ehsan Akbari

### Highlights

- ❖ Energy management should be implemented in the distribution network using an integrated PV-hydrogen storage system to improve the network's technical and financial performance.
- ❖ Modeling the distribution network's operational, economic, and environmental indicators concurrently as a multi-objective optimization problem. This methodology proficiently encapsulates the multi-criteria goals of the DSO, furnishing an all-encompassing structure for making decisions.
- ❖ The incorporation of a hydrogen storage system with PVs to offset variations in PV power, improving the integrated energy system's capacity to regulate network indices by doing so.

### Graphical Abstract



**Multi-Objective Energy Management Model**

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# Stochastic Scheduling of Integrated System of Solar Resources and Hydrogen Storage in the Smart Distribution Network Considering a Multi-Objective Energy Management Model

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## ABSTRACT

This study proposes an integrated framework that combines photovoltaic (PV) generation with hydrogen-based storage to enhance energy management in smart distribution systems. The framework is designed to address the multi-objective concerns of distribution system operators (DSOs), focusing on minimizing operating costs, reducing energy losses, and mitigating greenhouse gas emissions. To ensure technical rigor and practical applicability, the model incorporates alternating current (AC) power flow equations along with operational constraints and system-specific performance characteristics. Recognizing the inherent uncertainties associated with load demand, renewable PV output, and fluctuating market prices, the research employs a scenario-based stochastic optimization method. This approach integrates the Kantorovich method, which efficiently manages complex multi-dimensional problems, with the Roulette Wheel Mechanism (RWM), a probabilistic selection tool that enhances solution robustness under uncertainty. Numerical simulations validate the effectiveness of the proposed method, demonstrating significant improvements compared with conventional load flow analyses. The results show reductions of approximately 14.5% in operational costs, 28.9% in energy losses, and 21% in emissions, indicating the capacity of the approach to promote sustainable and cost-efficient system operation. Beyond its quantitative achievements, the study provides meaningful insights for DSOs, offering a structured roadmap to navigate the technical, economic, and environmental challenges posed by evolving energy systems. Ultimately, the research underscores the transformative potential of PV-hydrogen integration for building resilient, efficient, and environmentally responsible distribution networks, contributing both theoretical advancements and practical guidance to the broader discourse on sustainable energy management.

## 1. Introduction

### 1.1. Motivation

The global shift towards renewable energy sources (RES) has gained significant momentum in recent years, driven primarily by escalating environmental concerns associated with the extensive reliance on fossil fuels. This transition is not merely a trend but a necessary response to the pressing challenges posed by climate change and the depletion of non-renewable resources. Among the diverse array of RES technologies, photovoltaic (PV) systems stand out as particularly appealing options. Their advantages include relatively low land requirements, ease of installation, and scalability, which make them more accessible compared to other renewable alternatives such as wind or geothermal energy [1]. However, the increasing integration of PV systems into distribution networks presents a set of operational challenges that must be addressed to ensure the stability and reliability of the electrical grid. One significant issue is the potential for overvoltage conditions, which can arise when the generation from PV systems exceeds the local demand, particularly during peak sunlight hours. Additionally, the inherent intermittency and variability of solar energy introduce uncertainties that can lead to discrepancies between day-ahead forecasts and real-time operational conditions [2].

These mismatches often result in imbalances between electricity supply and demand, which can compromise the reliability of the power system and lead to potential disruptions. To mitigate these challenges, the integration of energy storage systems with PV technology has emerged as a highly effective solution. Storage systems can absorb excess energy generated during peak production periods and release it during times of low generation or high demand, thereby compensating for the fluctuations associated with solar energy production. This capability not only enhances the reliability of the power supply but also contributes to the overall stability of the distribution network [2]. Consequently, the implementation of effective energy management strategies within distribution networks has become increasingly essential. The coordinated operation of PV-storage systems in conjunction with the distribution system operator (DSO) represents a practical pathway toward optimizing network operations. Such coordination can lead to enhanced technical reliability, reduced environmental impacts, and improved economic performance. By strategically managing the interplay between generation, storage, and consumption, DSOs can facilitate a more resilient and efficient energy distribution system that aligns with the broader goals of sustainability and energy transition. In summary, as the world continues to embrace renewable energy technologies, the challenges associated with their integration into existing infrastructure must be proactively addressed. The development and implementation of innovative energy management strategies that leverage the synergies between PV systems and storage solutions will be critical in ensuring a reliable, sustainable, and economically viable energy future.

## 1.2. Literature review

A substantial body of research has been dedicated to the exploration of energy management within contemporary distribution networks, with scholars examining a wide array of technical, economic, and environmental dimensions under various operational conditions. For instance, the study presented in [3] delves into the analysis of expected energy not-supplied (EENS) and the voltage stability index (VSI) within the context of dynamic reconfiguration strategies in distribution networks. This research broadens its focus to encompass both balanced and unbalanced systems, while also addressing the critical integration of RES and energy storage systems (ESSs). Such contributions are pivotal in enhancing the resilience and stability of distribution operations, particularly as the energy landscape evolves. In another significant contribution, the concept of economic flexible–securable operation (EFSO) is introduced for smart distribution networks (SDNs) in [4]. This innovative formulation integrates distributed generation and storage resources to improve the delivery of environmentally sustainable electricity. The authors frame the problem as a constrained optimization task, aiming to minimize overall operational costs while simultaneously fulfilling requirements related to optimal power flow, environmental impact mitigation, system security, and operational flexibility. This multifaceted approach underscores the importance of balancing economic viability with environmental stewardship in the management of modern energy systems. Further advancing the discourse, the research in [5] focuses on optimizing the management of electric vehicle (EV) charging systems connected to distribution networks. The proposed model, which is primarily powered by solar and wind resources, categorizes EVs into four distinct groups based on their contributions to the grid. By employing the normal distribution function, the model captures the random spatial distribution of EVs while also accounting for the stochastic variability of wind speed and solar irradiation. This approach acknowledges the inherent intermittency and lack of coordination between renewable generation sources and EV demand, offering strategies to mitigate these challenges effectively. The work presented in [6] proposes a novel energy management framework aimed at determining the optimal operation of a grid-connected microgrid. This framework explicitly considers uncertainties associated with renewable-based distributed generation units, such as wind turbines (WTs) and PV systems, thereby ensuring a more reliable and practical operational scheme. Similarly, the research in [7] investigates energy management strategies for a microgrid integrated with battery charging and swapping stations. This study highlights the dual role of such infrastructure in facilitating renewable energy integration while simultaneously addressing the growing demand for EVs. In a shift towards real-time applications, [8] emphasizes the active participation of distribution networks in energy markets. The authors explore the coordinated use of price-responsive demand, inverter-based PV generation units, and battery energy storage systems (BESSs) within an active distribution network (ADN). This approach not only strengthens the role of distributed networks in dynamic energy trading but also enhances system flexibility and resilience, thereby contributing to a more robust energy ecosystem. Complementing this, [9] introduces a control framework based on multi-agent deep reinforcement learning (MADRL). By employing an actor–critic algorithm enhanced with a shared attention mechanism, this model adeptly manages energy flows in interconnected greenhouses, thereby extending the scope of energy management research to agricultural applications. Innovative optimization techniques have also been proposed to tackle the challenges associated with energy management in distributed systems. For example, [10] presents the Golden Jackal Optimization (GJO) algorithm, a nature-inspired metaheuristic designed to optimize distributed generation systems that comprise hybrid energy sources (HESs) and battery storage systems (BSSs). Similarly, [11] proposes a multi-objective tuna swarm optimization technique for active distribution networks. This method introduces enhancements in initialization, population diversity, and objective transformation, thereby enabling more effective solutions to the multi-objective optimization problems that characterize energy management. Collectively, these contributions underscore the diversity of methodologies employed to enhance energy management in distribution networks, ranging from classical optimization models and stochastic formulations to advanced artificial intelligence and bio-inspired metaheuristics. They highlight the increasing complexity of distribution systems in the context of renewable energy integration, storage technologies, and flexible loads. Furthermore, these studies emphasize the central role of optimization and intelligent control in ensuring the sustainability, reliability, and cost-effectiveness of modern energy systems. As the energy landscape continues to evolve, ongoing research in these areas will be crucial for developing innovative solutions that address the challenges and opportunities presented by the transition to a more sustainable energy future.

### 1.3. Research gaps and contributions

Despite the considerable advancements made in the field of energy management within distribution networks, existing research continues to exhibit several shortcomings that hinder its comprehensiveness and practical applicability. A significant gap in the literature is the predominant emphasis on economic and operational indicators, often at the expense of a thorough examination of the interplay with technical factors. In real-world scenarios, distribution networks are characterized by a complex interaction among technical, operational, economic, and environmental indicators. Improvements in one dimension do not necessarily yield positive outcomes in others; for instance, a reduction in operational costs may inadvertently lead to overvoltage conditions, which can subsequently increase power losses and compromise the overall reliability of the system. This underscores the critical need to incorporate multiple, and frequently conflicting, indices into the energy management problem, thereby ensuring a more holistic and realistic optimization framework. Another recurring limitation in the existing literature is the insufficient consideration of the co-location of renewable energy resources and storage systems. In many studies, distributed energy resources (DERs), such as PV units and storage devices, are modeled as being geographically dispersed across various buses within the network. However, when these components are co-located and integrated into a unified system, their synergistic interactions can significantly enhance both the economic and technical performance of the network. For example, the output power of a PV system can be effectively stabilized when combined with hydrogen storage, resulting in a more reliable and flexible operational framework. This potential for synergy remains largely underexplored in current research. Moreover, the majority of previous works have predominantly employed batteries as the primary storage technology within integrated energy systems. While batteries offer notable advantages, such as high power density and efficiency, they are also constrained by limitations, including relatively short operational lifespans, high installation costs, and challenges associated with scaling capacity. In contrast, hydrogen storage presents a promising alternative due to its extended operational life, lower installation costs, and favorable efficiency characteristics. Despite these advantages, the integration of hydrogen storage with PV systems has received limited attention in the literature, leaving a significant research avenue largely unexplored. To address these identified gaps, the present study investigates the energy management of a smart distribution network that incorporates an integrated PV-hydrogen storage system. The proposed framework explicitly models the technical, economic, and environmental objectives of the DSO within a multi-objective optimization formulation. This design is constrained by the operational model of the integrated PV-hydrogen storage system, network operational limits, and the AC power flow equations, ensuring that the model adheres to practical operational realities. To effectively capture uncertainties related to load demand, energy prices, and renewable power generation, a scenario-based stochastic optimization (SBSO) approach is employed. This method allows for a more robust analysis of potential future states of the system, accommodating the inherent variability associated with renewable energy sources. Furthermore, fuzzy decision-making techniques are applied to identify compromise solutions that systematically balance conflicting objectives, thereby facilitating a more nuanced approach to energy management.

In summary, this study aims to contribute to the existing body of knowledge by providing a comprehensive framework that addresses the multifaceted challenges of energy management in distribution networks. By integrating an innovative PV-hydrogen storage system and employing advanced optimization techniques, the research seeks to enhance the operational efficiency, reliability, and sustainability of modern energy systems, ultimately paving the way for more resilient and adaptable distribution networks in the face of evolving energy demands.

The novel contributions of this research are summarized as follows:

- Implementation of integrated PV–hydrogen storage systems for energy management in distribution networks, thereby improving both the technical reliability and the financial performance of the network.
- Concurrent modeling of operational, economic, and environmental indicators within a unified multi-objective optimization problem, providing the DSO with a comprehensive decision-making framework.
- Integration of hydrogen storage with PV systems to mitigate PV output variability and enhance the network's ability to regulate key operational indices.

The remainder of this paper is organized as follows: [Section 2](#) presents the detailed modeling of the proposed strategy as a multi-objective optimization problem. [Section 3](#) introduces the stochastic optimization framework for modeling uncertainties. [Section 4](#) analyzes the numerical results obtained from several case studies, and [Section 5](#) concludes the paper with a discussion of the findings and their implications.

## 2. Formulation

This section delineates the proposed framework for energy management within a distribution network that incorporates an integrated PV and hydrogen storage system. The strategy is meticulously designed to simultaneously address the operational, economic, and environmental objectives of the DSO, thereby offering a balanced and comprehensive approach to energy management. The formulation of this framework is subject to several technical constraints, which are critical for ensuring the integrity and reliability of the system. Among these constraints, the AC power flow equations play a pivotal role in governing the dynamics of the distribution network. These equations are essential for accurately modeling the flow of electrical power through the network, taking into account the voltage levels, phase angles, and power losses that occur during transmission. Additionally, the operational characteristics of the integrated PV-hydrogen storage system are incorporated into the model, ensuring that the unique performance attributes of these technologies are adequately represented. By imposing these constraints, the optimization framework is designed to remain both technically feasible and practically applicable in real-world scenarios. This ensures that the solutions generated by the model are not only theoretically sound but also implementable within the existing infrastructure of the distribution

network. The mathematical formulation of the proposed model is presented as follows in Equation (1-19):

$$\min F = v_1 \text{Cost} + v_2 \text{EL} + v_3 \text{EM} \quad (1)$$

Subject to:

$$\text{Cost} = \sum_{t,w} \pi_w p_{t,w} P_{b=r,t,w}^{DS} \quad (2)$$

$$\text{EL} = \sum_{t,w} \pi_w (P_{b,t,w}^{DS} + P_{b,t,w}^I - P_{b,t,w}^C) \quad (3)$$

$$\text{EM} = \sum_{t,w} \pi_w (\text{CO}_2 + \text{SO}_2 + \text{NO}_x) P_{b=r,t,w}^{DS} \quad (4)$$

$$P_{b,t,w}^{DS} + P_{b,t,w}^I + \sum_j A_{b,j} P_{b,j,t,w}^L = P_{b,t,w}^C \quad \forall b, t, w \quad (5)$$

$$Q_{b,t,w}^{DS} + \sum_j A_{b,j} Q_{b,j,t,w}^L = Q_{b,t,w}^C \quad \forall b, t, w \quad (6)$$

$$P_{b,j,t,w}^L = G_{b,j}^L (V_{b,t,w})^2 - V_{b,t,w} V_{j,t,w} \{G_{b,j}^L \cos(\varphi_{b,t,w} - \varphi_{j,t,w}) + B_{b,j}^L \sin(\varphi_{b,t,w} - \varphi_{j,t,w})\} \quad \forall b, j, t, w \quad (7)$$

$$Q_{b,j,t,w}^L = -B_{b,j}^L (V_{b,t,w})^2 + V_{b,t,w} V_{j,t,w} \{B_{b,j}^L \cos(\varphi_{b,t,w} - \varphi_{j,t,w}) - G_{b,j}^L \sin(\varphi_{b,t,w} - \varphi_{j,t,w})\} \quad \forall b, j, t, w \quad (8)$$

$$\varphi_{b,t,w} = 0 \quad \forall b = r, t, w \quad (9)$$

$$V_{b,t,w} = 1 \quad \forall b = r, t, w \quad (10)$$

$$V_b^{\min} \leq V_{b,t,w} \leq V_b^{\max} \quad \forall b, t, w \quad (11)$$

$$\sqrt{(P_{b,j,t,w}^L)^2 + (Q_{b,j,t,w}^L)^2} \leq S_{b,j}^{L,\max} \quad \forall b, j, t, w \quad (12)$$

$$\sqrt{(P_{b,t,w}^{DS})^2 + (Q_{b,t,w}^{DS})^2} \leq S_b^{DS,\max} \quad \forall b = r, t, w \quad (13)$$

$$P_{b,t,w}^I = P_{b,t,w}^{PV} + (P_{b,t,w}^{DCH} - P_{b,t,w}^{CH}) \quad (14)$$

$$P_{b,t,w}^{PV} = \mu_{t,w} P_b^{PV,\max} \quad \forall b, t, w \quad (15)$$

$$0 \leq P_{b,t,w}^{DCH} \leq DR_b x_{b,t} \quad \forall b, t, w \quad (16)$$

$$0 \leq P_{b,t,w}^{CH} \leq CR_b (1 - x_{b,t}) \quad \forall b, t, w \quad (17)$$

$$E_{b,t,w} = E_b(0) + \sum_{t,w} (\eta^{CH} P_{b,t,w}^{CH} - \frac{1}{\eta^{DCH}} P_{b,t,w}^{DCH}) \quad \forall b, t, w \quad (18)$$

$$E_b^{\min} \leq E_{b,t,w} \leq E_b^{\max} \quad (19)$$

The objective of the proposed framework is to minimize a weighted sum of three key performance measures in the distribution network: total operational cost, energy losses, and environmental emissions. This goal is expressed in Equation (1). The projected cost of the distribution network (Cost) is defined in Equation (2) [1]. Anticipated energy losses (EL), defined as the difference between energy consumed and energy produced, are formulated in Equation (3). Equation (4) models network emissions (EM), which result from the upstream energy supply. Specifically, emissions from SO<sub>2</sub>, NO<sub>x</sub>, and CO<sub>2</sub> are considered in this work [12].

The weighted combination of these three performance measures constitutes the overall objective function (F). The associated weight coefficients are denoted by v<sub>1</sub>, v<sub>2</sub>, and v<sub>3</sub>. By varying these coefficients, different trade-offs between Cost, EL, and EM can be achieved, thereby generating multiple Pareto-optimal solutions. The resulting Pareto front of the proposed scheme is obtained by plotting these functions in three-dimensional space [13].

To determine the optimal compromise solution, a fuzzy decision-making approach is applied. First, the minimum and maximum values of each function are determined by setting v<sub>1</sub> = 1, v<sub>2</sub> = 1, and v<sub>3</sub> = 1 in turn. A linear membership function (f<sub>i</sub>) is then defined. For a given set of weight coefficients, f<sub>i</sub> = 0 if the function value exceeds F<sub>max</sub>, and f<sub>i</sub> = 1 if the function value is less than F<sub>min</sub>. Otherwise, f<sub>i</sub> is calculated as (f - F<sub>max</sub>)/(F<sub>min</sub> - F<sub>max</sub>), where f is the actual function value. This procedure is repeated for the Cost, EL, and EM functions. The minimum f<sub>i</sub> among them is selected, and the corresponding weight coefficients are adjusted. For each Pareto front solution, the value of σ and the associated f<sub>i</sub> are calculated. Ultimately, the compromise solution is defined as the Pareto front point with the maximum σ value [13].

The optimization problem under consideration is further constrained by a series of technical and operational limitations that are critical for ensuring the feasibility and reliability of the system. Specifically, Equations (5) to (10) delineate the AC power flow equations pertinent to the distribution network. These equations encompass essential parameters such as the angles and magnitudes of bus voltages, as well as the active and reactive power flows traversing the distribution lines [1,3]. The integrity of the power distribution system is contingent upon adhering to these equations, which are fundamental to the analysis of power systems.

In addition to the power flow equations, Equations (11) to (13) encapsulate various operational restrictions that must be observed. These include the bounds on bus voltage magnitudes, as articulated in Equation (11), which ensures that voltage levels remain within acceptable limits to prevent equipment damage and maintain system stability. Furthermore, Equation (12) imposes limits on the apparent power flow across distribution lines, thereby safeguarding against overloading and ensuring efficient operation. Lastly, Equation (13) addresses the capacity constraints of the substation, which is pivotal for maintaining the overall reliability of the distribution network. It is noteworthy that the network is assumed to comprise a singular distribution substation that is interconnected with the upstream grid at the reference bus. Consequently, for the purposes of analysis, the bus index *b* is set equal

to the reference bus  $r$  in Equations (2), (4), and (13), thereby simplifying the representation of the network.

The operational constraints governing the integrated PV and hydrogen storage system are articulated through Equations (14) to (19). Equation (14) serves to regulate the net electricity exchanged between the distribution network and the PV-hydrogen storage system, thereby facilitating a balanced energy exchange that is essential for system stability. In Equation (15), the generation of electricity from the PV system is quantified as the product of the installed PV capacity and the PV power rate [2]. This relationship is crucial for accurately modeling the contribution of solar energy to the overall energy mix.

The operational dynamics of the hydrogen storage system are further constrained by Equations (16) to (19) [14]. Specifically, Equations (16) to (17) delineate the power limits for both charging and discharging processes, respectively, while simultaneously ensuring that these two processes cannot occur concurrently. To facilitate this operational logic, a binary decision variable  $x$  is introduced, where  $x=0$  signifies that the system is in charging mode, and  $x=1$  indicates that it is in discharging mode. This binary variable is instrumental in modeling the operational state of the hydrogen storage system.

Equation (18) provides a mathematical representation of the state of charge of the hydrogen storage system, which is updated based on the initial energy stored, the net energy charged, and the energy discharged. This dynamic modeling is essential for accurately tracking the energy balance within the storage system. Finally, Equation (19) stipulates the maximum storage capacity, thereby ensuring that the system operates within its physical limits and maintains operational integrity. Collectively, these constraints form a comprehensive framework that governs the optimization problem, ensuring that both technical and operational requirements are met in the design and operation of the integrated PV-hydrogen storage system.

### 3. Modeling Uncertainties

In the proposed framework, several parameters in Equations (1) to (19), including load demand ( $P^c$  and  $Q^c$ ), energy price ( $p$ ), and PV power production rate ( $\mu$ ), are subject to uncertainty. To ensure a reliable solution capable of addressing the prediction errors associated with these uncertain variables, this study employs a SBSO approach. The adopted SBSO method integrates the Kantorovich technique with the RWM [15].

In this procedure, a large number of scenarios are first generated using the RWM. For each scenario, the probability of the selected values for the load and energy price is determined using a normal probability distribution, while the PV production rate is modeled with a beta probability distribution. Consequently, the probability of each generated scenario, denoted as  $\pi^0$ , is obtained as the product of the individual probabilities of the uncertainties.

To reduce the computational burden, the Kantorovich approach is applied as a scenario-reduction technique. This method identifies and retains a representative subset of scenarios that are most similar to one another, thereby maintaining the essential probabilistic characteristics of the original set while improving computational efficiency. The optimization problem defined in Equations (1) to (19) is then solved using this reduced scenario set.

Finally, the probability of each selected scenario is recalculated as the ratio of its corresponding  $\pi^0$  value to the sum of  $\pi^0$  values across all retained scenarios. This ensures that the reduced scenario set preserves the probabilistic integrity of the original uncertainty model [15].

### 4. Numerical Results

#### 4.1. Data

The proposed methodology is validated using the IEEE 33-bus distribution network [16], illustrated in Figure 1. The system operates with a base voltage of 12.66 kV and a base apparent power of 1 MVA. The distribution substation, located at Bus 1 (the reference bus), connects the distribution network to the upstream transmission system. The permissible voltage range at all buses is restricted between 0.90 and 1.05 p.u. Peak active and reactive load values for each bus, as well as distribution line and substation parameters, are adopted from [16].

The actual hourly load demand is obtained by multiplying the peak load values by the daily load factor curve, as shown in Figure 2 [1]. The energy price structure of the system is time-dependent and follows a three-tier tariff scheme [1]:

- 01:00–07:00: \$16/MWh
- 17:00–22:00: \$30/MWh
- All other hours: \$24/MWh

Additionally, emissions associated with electricity purchased from the upstream network are considered. The emission coefficients of the major pollutants are as follows [12]:

- $CO_2$ : 764.3 ton/MWh
- $SO_2$ : 2.4 ton/MWh
- $NO_x$ : 0.7 ton/MWh

This test system provides a realistic basis for evaluating the operational, environmental, and economic impacts of the proposed PV–hydrogen storage integration and energy management framework.

This network has six integrated PV-hydrogen storage systems, as shown in Figure 1, where the locations of various energy systems are given. Every system consists of 0.6 MW worth of PVs. Figure 2 [1] shows the predicted power generation rate curve of the PV. Note that, 2 MWh hydrogen storage with beginning and minimum energy levels set at 0.2 MWh is also included with each system. The hydrogen storage is anticipated to have a 0.6 MW charge and discharge rate, with a 93% charge and discharge efficiency [14].

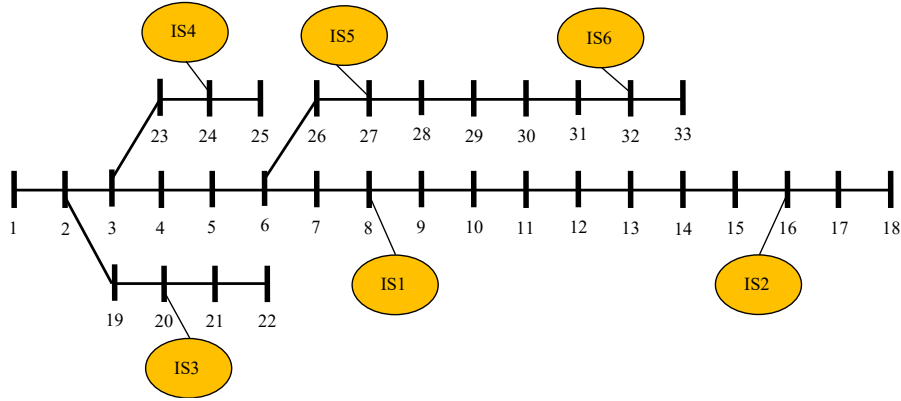


Figure 1. IEEE 33-bus distribution network [16] along with integrated PV-hydrogen storage units.

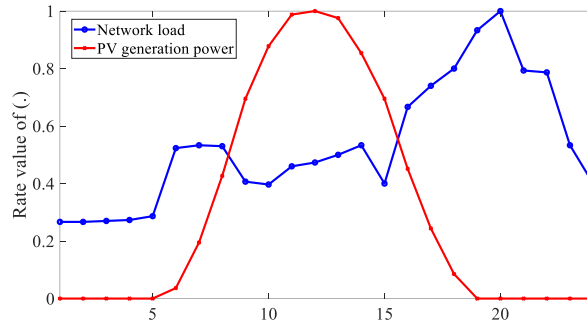


Figure 2. Expected daily curve of load factor and PV power generation rate [1].

4.2. Results and discussion

This part uses the GAMS optimization software environment to encode the problem given by Equations (1) to (19), which correspond to the data provided in section 4.1. A Mixed Integer Non-Linear Programming (MINLP) issue is how this one is classified. To solve it, the BONMIN algorithm [17] is used.

A) *Evaluation of Multi-Objective Energy Management in the Distribution Network:* The Pareto front of the proposed strategy at a 100% load level is summarized in Table 1. As observed, the trends of the objective functions—Cost, Energy Loss (EL), and Emissions (EM)—do not follow the same pattern. Specifically, cost minimization is often associated with an increase in EL. This is primarily because achieving lower costs requires the combined PV–hydrogen storage system to inject a considerable amount of active power into the network. Consequently, reverse power flow toward the distribution substation may occur, leading to higher current magnitudes and, therefore, greater energy losses.

According to Table 1, the minimum achievable values of Cost, EL, and EM are \$894.2, 1.12 MWh, and 21.3 tons, respectively. Conversely, their maximum values are \$3612.1, 2.61 MWh, and 38.4 tons, respectively. Hence, the ranges of variation are \$2717.9 for Cost, 1.49 MWh for EL, and 17.1 tons for EM. Employing fuzzy decision-making methodologies, the optimal compromise solution across a spectrum of load levels is systematically detailed in Table 2. At the 100% load level, the identified compromise point yields specific values of \$1289.3 for Cost, 1.55 MWh for EL, and 24.9 tons for EM. These metrics are critical as they reflect the trade-offs inherent in the optimization process, where multiple objectives must be balanced to arrive at a satisfactory solution. A thorough comparative analysis between Tables 1 and 2 reveals significant insights regarding the performance of the compromise solution relative to the optimal points. Specifically, the deviation of the compromise solution from the minimum point is quantified as 14.5% for Cost, 21% for EL, and 28.9% for EM. These percentages indicate that while the compromise solution is not the absolute optimal solution, it is strategically positioned in close proximity to the optimal values. This proximity suggests that the selected compromise effectively balances the competing objectives of minimizing costs, reducing energy losses, and lowering emissions, thereby reflecting a well-considered trade-off among these critical factors. Moreover, the results encapsulated in Table 2 provide compelling evidence that all three functions—Cost, EL, and EM—exhibit a discernible increasing trend as load levels rise. This trend can be attributed to the intensified utilization of the distribution network, which inherently amplifies both technical and environmental impacts under conditions of heightened demand. As the load increases, the distribution network experiences greater stress, leading to increased energy losses due to resistance in the lines and higher emissions resulting from the additional energy generation required to meet the demand. The implications of these findings are significant for stakeholders involved in energy management and policy-making. They underscore the necessity of considering the interplay between load levels and the associated impacts on cost, energy loss, and

emissions. In particular, the results highlight the importance of developing strategies that not only aim for cost efficiency but also prioritize sustainability and environmental stewardship. In conclusion, the application of fuzzy decision-making in this context not only facilitates the identification of a compromise solution that is close to optimal but also emphasizes the critical need for a holistic approach to energy management. By acknowledging the trade-offs among cost, energy loss, and emissions, decision-makers can better navigate the complexities of energy distribution and contribute to a more sustainable energy future.

B) *Performance of integrated PV- hydrogen storage systems:* The operational behavior of the integrated PV–hydrogen storage system across different load levels is illustrated in Figure 3, which presents the predicted daily active power curves of the PV units and hydrogen storage. As shown in Figure 3(a), the daily PV power generation profile closely follows the general trend depicted in Figure 2, reflecting the typical solar irradiance pattern. In this context, the PV units are able to operate at their full rated capacity during peak sunshine hours, which corresponds to the constraints defined in Equation (15). The complementary operation of hydrogen storage is highlighted in Figure 3(b). During the early hours of the day, specifically from 01:00 to 16:00, the hydrogen storage units predominantly remain in charging mode, with the highest charging demand occurring between 01:00 and 07:00. This period coincides with the lowest electricity prices, making it economically advantageous for the storage system to absorb power and minimize overall costs. Conversely, during the evening peak hours from 17:00 to 22:00, when energy prices reach their maximum, the hydrogen storage units transition into discharge mode. In this phase, they inject a significant amount of power into the network, thereby reducing both operating costs and emissions. Furthermore, from 08:00 to 16:00, the hydrogen storage is also occasionally switched to discharge mode in response to high PV generation levels. This strategy helps mitigate the risk of overvoltage that may arise from the injection of surplus PV power into the grid. The aggregated active power profile of the combined PV–hydrogen storage system for different load conditions is presented in Figure 4. According to Equation (14), this profile is calculated as the summation of PV generation and hydrogen storage discharge power, minus the hydrogen storage charging power. The results reveal that during the low-price period (01:00 to 07:00), the system predominantly behaves as a consumer, as the hydrogen storage absorbs power while PV generation remains minimal. For the remaining hours of the day, the system operates as a net producer, supplying power through both PV generation and storage discharge. In mathematical terms, the aggregated active power profile can be expressed as  $P_{total} = P_{PV} + P_{discharge} - P_{charge}$ , where,  $P_{total}$  is the total active power,  $P_{PV}$  is the power generated by the PV units,  $P_{discharge}$  is the power discharged from the hydrogen storage,  $P_{charge}$  is the power absorbed by the hydrogen storage.

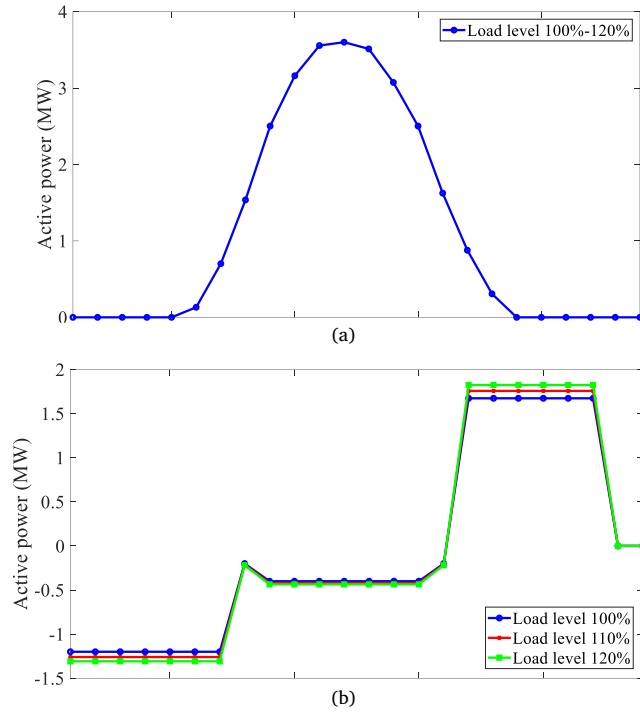
This equation encapsulates the dynamic interaction between the PV generation and hydrogen storage, highlighting the system's ability to adapt to varying load conditions and electricity prices. An important observation is that the PV daily generation curve remains unchanged across different load levels, as it is solely dependent on solar irradiance and independent of network demand. By contrast, the operation of the hydrogen storage system is highly responsive to load variations. As the load level increases, both charging and discharging capacities of the hydrogen storage expand, thereby amplifying the system's contribution in both consumption and generation modes. Consequently, the integrated PV–hydrogen storage system demonstrates enhanced flexibility and adaptability, offering improved support to the distribution network under varying load conditions.

**Table 1.** Pareto front of the suggested plan for a load level of 100%.

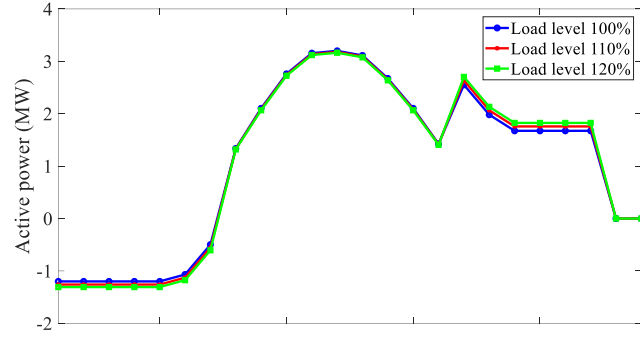
$v_1$	$v_2$	$v_3$	Cost (\$)	EL (MWh)	EM (ton)
1	0	0	894.2	2.61	33.4
0	1	0	3612.1	1.12	38.4
0	0	1	2932.4	2.48	21.3
0.75	0.25	0	1145.6	2.18	35.3
0.75	0	0.25	1008.5	2.49	28.8
0.25	0.75	0	2198.1	1.97	36.7
0	0.75	0.25	3252.5	1.86	34.2
0.25	0	0.75	3025.2	2.41	25.3
0	0.25	0.75	2989.1	2.81	26.4
0.5	0.5	0	1431.2	2.05	35.8
0.5	0	0.5	1344.1	2.51	26.8
0	0.5	0.5	3068.9	2.03	26.5
0.33	0.33	0.33	1678.2	2.31	27.1

**Table 2.** Optimal compromise solution between the Cost, Energy Loss (EL), and Emissions (EM) functions under different load levels.

Load level (%)	Cost (\$)	EL (MWh)	EM (ton)
100	1289.3	1.55	24.9
110	1307.1	1.71	27.0
120	1418.6	1.85	29.1



**Figure 3.** Predicted daily curves of the integrated PV–hydrogen storage system at different load levels: (a) PV power generation profile, showing consistency with the irradiance-based trend; (b) hydrogen storage charging and discharging patterns, highlighting load-dependent operation and price-responsive scheduling.



**Figure 4.** Predicted daily active power profile of the combined PV–hydrogen storage system under various load levels, computed as the net power (PV generation plus hydrogen discharge minus hydrogen charge), indicating the transition from consumer behavior during low-price hours (01:00–07:00) to net producer behavior during the remaining hours.

C) *Evaluation of the technical, economic, and environmental status of the distribution network:* The economic (Cost), environmental (EM), operational (EL), maximum voltage drop (MVD), and maximum overvoltage (MOV) indicators for the 100% load level are summarized in Table 3 across three case studies: Case I (base network without PV or storage), Case II (PV-only integration), and Case III (integrated PV–hydrogen storage system). As shown in the table, Case I yields the highest values of Cost, EM, EL, and MVD, since all energy is supplied by the upstream network. Introducing PVs into the distribution network (Case II) reduces all indicators compared to Case I, except for MOV, which increases due to voltage rise effects. In Case III, the integrated PV–hydrogen storage system achieves the most significant reductions in Cost, EL, EM, and MOV relative to Case I, demonstrating its effectiveness in improving system performance. Additionally, peak load carrying capacity (PLCC)—an operational index representing the maximum load the network can support under the daily load factor curve of Figure 2—remains unchanged between Cases I and II, as PVs are inactive during the peak load hour (20:00). However, in Case III, PLCC is notably higher due to hydrogen storage’s substantial power injection during peak hours (17:00–22:00).

**Table 3.** Comparison of economic (Cost), environmental (EM), operational (EL), maximum voltage drop (MVD), maximum overvoltage (MOV), and peak load carrying capacity (PLCC) indicators across three scenarios (Case I: base network, Case II: PV-only integration, Case III: integrated PV–hydrogen storage system) at 100% load level.

Index	Parameter	Case I	Case II	Case III
Economic	Cost (\$)	3971.2	1404.3	1289.3
Environment	EM (ton)	48.9	25.8	24.9
Operation	EL (MWh)	3.12	1.67	1.55
	MVD (p.u.)	0.087	0.051	0.048
	MOV (p.u.)	0	0.024	0.011
	PLCC (MW)	3.715	3.715	4.59

**5. Conclusion**

This study investigated the energy management of a distribution network with a focus on the operational, economic, and environmental objectives of the DSO in the context of integrated PV–hydrogen storage systems. The proposed framework, constrained by optimal power flow equations and the operational model of the network, aimed to minimize a weighted sum of operating costs, energy losses, and emissions. To address uncertainties in load demand, PV generation, and electricity prices, a stochastic optimization approach was employed, and fuzzy decision-making was applied to identify the best compromise solution. The numerical results demonstrated that this compromise point maintains the values of operating cost, energy losses, and emissions within 14.5%, 28.9%, and 21% of their respective minimum values, ensuring a near-optimal balance across objectives. Comparative analysis revealed that integrating PV systems alone can reduce maximum voltage drop, emissions, costs, and energy losses; however, this improvement is offset by a substantial increase in overvoltage. By contrast, the incorporation of hydrogen storage alongside PV generation not only alleviates the overvoltage issue but also provides the most significant enhancements across operational, environmental, and economic indicators. Demand-side management (DSM) is one of the promising energy management strategies that can enhance both the technical and economic performance of distribution networks. Incorporating DSM into the proposed framework is therefore suggested as a direction for future research. In addition, EVs are emerging as significant new consumers whose charging behavior directly influences network operation. Effective management of EV demand can provide valuable operational flexibility and improve network performance. Consequently, integrating EVs into the proposed scheme is also identified as an important avenue for future work.

**Nomenclature**

Indices	
$b, t, w, r$	Bus, Operating Hour, Scenario, Reference Bus
$j$	Auxiliary Index Corresponding to the Bus
Variables	
$Cost, EL, EM$	Expected Network Operation Cost (\$), Expected Network Energy Losses (MWh), Network Pollution Level (ton)
$E$	Energy Stored in hydrogen tank (MWh)
$F$	Objective Function
$P^{PS}, P^A, P^D, P^{PV}, P^{CH}, P^{DCH}$	Active Power Passing Through Distribution Substation and Distribution Line, Active Power of Integrated PV-Hydrogen Storage System, PV Active Power, Active Power of Hydrogen Storage in Charge and Discharge Modes (MW)
$Q^{RS}, Q^C$	Reactive Power Passing Through the Distribution Substation and Distribution Line (MVar)
$V, \varphi$	Voltage Amplitude (p.u.) and Voltage Angle (rad)
$x$	Binary Variable Corresponding to Hydrogen Storage Charge/Discharge Operation
Parameters	
$A, G, B$	Cross Matrix of Bus, Distribution Line Conductance (p.u.), Distribution Line Susceptance (p.u.)
$CO_2, SO_2, NOX$	Pollution Coefficients (ton/MWh)
$CR, DR$	Charge and Discharge Rate of Hydrogen Storage (MW)
$E(0), E^{min}, E^{max}$	Primary Energy, Minimum and Maximum Energy Stored in Hydrogen Storage (MWh)
$p$	Energy Price (\$/MWh)
$P^C, Q^C$	Active Power (MW) and Reactive Power (MVar) of the Load
$P^{PV,max}$	PV Capacity (MW)
$S^{L,max}, S^{DS,max}$	Maximum Apparent Power of Distribution Line and Distribution Substation (MVA)
$V_D, V_{D0}, V_S$	Weight Coefficients in the Objective Function
$V^{min}, V^{max}$	Minimum and Maximum Voltage Magnitude (p.u.)
$\pi, \mu$	Scenario Probability, PV Power Generation Rate
$\eta^{CH}, \eta^{DCH}$	Charge and Discharge Efficiency

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## Declaration of competing interest

The author declares that there are no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All ethical standards, including avoidance of plagiarism, informed consent, research misconduct, data fabrication or falsification, duplicate publication or submission, and redundancy, have been fully observed by the author.

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