Optimizing Solar Power Distribution in Microgrids: Reducing Energy Waste through Accurate Solar Power Prediction

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Abstract. The optimal distribution of solar power in microgrids is crucial for maximizing energy efficiency and minimizing waste. This paper proposes an optimization-based approach for solar power distribution in microgrids, considering both predicted solar energy and actual solar generation. The objective is to optimally distribute solar power among homes in a microgrid while ensuring minimal energy waste. The optimization model is formulated to minimize the squared difference between the distributed power and the demand of each home, subject to constraints on the total distributed power and individual home demands. The distribution technique considers the proportionate share of actual solar generation based on the predicted solar energy distribution. The impact of the accuracy of the solar power forecasting model on energy waste reduction is investigated through numerical experiments. The results demonstrate that the energy waste decreases once the accuracy of the forecasting model increases, highlighting the importance of accurate predictions in achieving efficient solar power distribution.

Keywords: Microgrid, solar power, optimization, energy distribution, sustainability

1 Introduction

The global shift towards clean and sustainable energy sources has driven the widespread integration of renewable energy systems in various sectors. Solar power, in particular, has emerged as a prominent and environmentally friendly energy solution due to its abundant availability and potential for reducing carbon emissions. Microgrids[1], as localized energy distribution networks, have gained significant attention as an effective means of incorporating renewable energy sources and enhancing energy resilience at a local level.

Microgrids operate as self-contained systems that function independently or in conjunction with the primary power grid. They consist of distributed energy resources (DERs), such as solar panels, wind turbines, and energy storage systems, along with advanced control mechanisms to manage and optimize energy flow. These microgrids provide several advantages, including improved energy efficiency, reduced transmission losses, increased reliability, and integration of renewable energy sources into the existing infrastructure.

However, the intermittent nature of renewable energy sources, such as solar power, poses unique challenges in optimizing energy distribution within microgrids. The fluctuating solar irradiance and varying energy demands of individual homes or buildings make it crucial to develop efficient strategies for solar power allocation. An optimized approach is required to allocate the available solar power among different loads or consumers within the microgrid to maximise the utilisation of solar energy and minimise energy waste. Optimization-based techniques, combined with machine learning algorithms, have emerged as practical tools for addressing the challenges of solar power distribution in microgrids. These approaches leverage historical data, weather patterns, and energy consumption patterns to predict solar energy generation and optimize its distribution among the connected loads. By considering factors such as predicted solar energy, actual solar generation, and individual load requirements, these techniques aim to minimize energy waste, maximize self-consumption, and improve the overall performance of microgrid systems. This paper proposes an optimized solar power distribution technique for microgrids that incorporates both predicted solar energy and actual solar generation data. Our approach focuses on achieving an optimal allocation of solar power among homes or loads within the microgrid, considering individual energy demands and minimizing energy waste.

The main objectives of this research are as follows:

- Develop an optimization model considering predicted solar energy and actual solar generation for efficient power distribution within microgrids.
- Formulate an objective function that minimizes energy waste by optimizing the allocation of solar power based on individual load requirements.
- Investigate the influence of the accuracy of the solar power forecasting model on reducing energy waste and improving overall system performance.
- Implement and evaluate the proposed solar power distribution technique through numerical simulations and analysis.

The remainder of this paper is structured as follows: Section 2 provides a brief literature survey, Section 3 provides a detailed methodology of the proposed optimization-based solar power distribution technique. Section 4 gives a detailed overview of the experimental setup, and Section 5 presents the simulation results of our proposed method. The Discussions are presented in Section 6. Finally, Section 7 concludes the paper by emphasizing the significance of the proposed approach in optimizing solar power distribution, minimizing energy waste, and fostering sustainable energy management within microgrids.

2 Literature Survey

Leonori et al.[8] in their paper explores energy management systems (EMSs) for grid-connected microgrids, focusing on Fuzzy Inference Systems (FISs) and

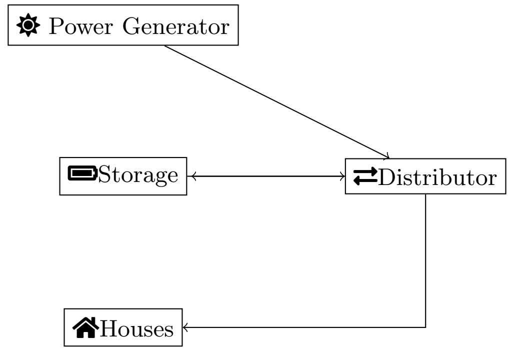

Fig. 1. Microgrid Block Diagram

hierarchical Genetic Algorithms (GAs). The objective is to maximize profit from grid energy exchange under a TOU pricing policy while reducing EMS complexity. Results show that the proposed approach achieves performance close to the ideal solution with a compact rule base. Bukar et al.[3] proposes a rule-based energy management system (EMS) optimized by a grasshopper optimization algorithm (GOA) for capacity planning of off-grid microgrids. The proposed technique minimizes the energy cost and power supply probability deficiency, outperforming particle swarm optimization (PSO) and cuckoo search algorithm (CSA). The results demonstrate in achieving cleaner energy production and reducing costs. Tooryan et al.[9] presents an optimization solution using Particle Swarm Optimization for a hybrid residential microgrid. The proposed method aims to minimize total costs, reduce environmental emissions, and increase renewable energy penetration. The results demonstrate a 35% reduction in CO2 emissions and improved system performance through the optimal installation of DER units. Haidar et al.[5] proposes an optimal strategy considering dynamic energy pricing, system uncertainties, and operational feasibility for evaluating hybrid microgrid configurations in rural areas of Sarawak, Malaysia. The results highlight the optimal configuration with the lowest cost, including solar PV, energy storage, hydro generation, environmental impact, and voltage security considerations. In their study Barbar et al[2] proposes an optimized design for the energy system of Faial Island in the Azores archipelago, aiming for high renewable energy penetration while considering feasibility constraints. A model combining weather and demand data is used to size the components of a hybrid energy system. The results suggest a system design with geothermal power, BESS capacity, thermal generators, and wind turbines, demonstrating robustness through Monte Carlo simulations. Kharrich et al.[7]addresses the sizing problem of a hybrid microgrid system with multiple renewable energy resources. Three multi-objective optimization algorithms (MOPSO, PESA II, and SPEA2) are compared using the Six Sigma approach. The objective functions considered are Net Present Cost, emission penalty cost, and CO2 quantity, subject to reliability, availability, and renewable fraction constraints. Feasibility is evaluated through LCOE and dumped energy calculations. Results indicate that SPEA2 is the preferred algorithm, achieving a competitive cost of energy and meeting all constraints while emphasizing reliability and availability. Hossain et al.[6]focuses on optimal energy management of a community microgrid considering the degradation cost of the battery and a dynamic penalty for operational cost. Particle swarm optimization (PSO) is utilized for real-time battery control actions. Case studies highlight the effectiveness of the proposed framework, achieving electricity cost reductions of up to 44.50% compared to a baseline method and 37.16% compared to another existing approach. The research emphasizes the significance of battery storage in microgrid optimization for cost savings and enhanced operational efficiency. In their study, Dahiru et al.[4] address the challenge of intermittent renewable energy in demand-side management for distributed grid technologies. It proposes a time-of-use fitness approach in a grid-connected photovoltaic/wind/battery nano grid to reduce energy costs while maintaining customer comfort. The method optimizes three nano grid configurations using nested integer linear programming and considers real-time residential consumption, renewable generation, and main grid imported power. The results demonstrate significant reductions in energy consumption costs compared to flat and conventional time-of-use rates, further improved by using the battery in binary states of operation. Expanding the operational scenarios of the battery can enhance the method's performance. Aguera et al.[1] highlights the importance of weather forecasts in microgrid energy management systems and their impact on optimal planning and scheduling. The study discusses similarities and differences with other energy forecast applications and offers recommendations for future implementations of weather forecasts in microgrid energy management systems.

3 Proposed Methodology

Our proposed Optimization-Based Distribution strategy[2] has mainly 2 steps as follows:

- Optimization based on forecasting
- Solar Power optimal Distribution

3.1 Optimization based on forecasting

In our proposed methodology, we aim to optimize solar power distribution within a microgrid, considering both predicted solar energy and actual solar generation. The objective is to minimize energy waste by allocating the available solar power among different loads or consumers optimally. To achieve this, we formulate an optimization problem that considers individual load requirements, predicted solar energy, and the actual solar generation.

Let's define the following variables:

- N: Total number of homes or loads within the microgrid.

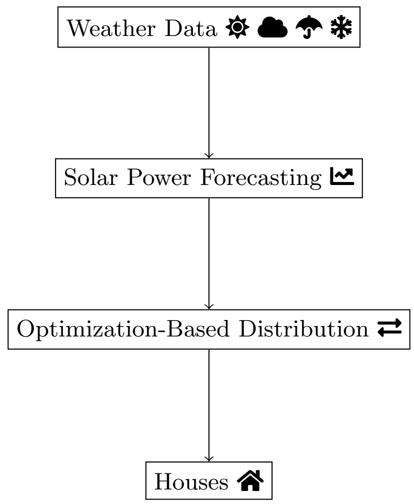

Fig. 2. Flow chart of the complete forecasting and distribution system

- D_i: Demand of home i, where $i \in [1, N]$.
- S: Predicted solar energy available within the microgrid.
- G: Actual solar generation within the microgrid.
- x_i: Solar power distributed to home i.

The overall problem can be formulated as below:

$$\min \sum_{i=1}^{N} (x_i - D_i)^2 \tag{1}$$

$$\sum_{i=1}^{N} x_i = S \tag{2}$$

$$x_i \leq D_i \quad \forall i \in [1, N] \tag{3}$$

The equation [1] denotes the objective function of the problem which aims to minimize the energy waste by minimizing the squared difference between the distributed power and the demand of each home, equation [2] is the first constraint which ensures that the total distributed power equals the predicted solar energy, while equation [3] is second constraint ensures that the distributed power does not exceed the demand of each home.

By solving this optimization problem, we can obtain an optimal distribution of solar power among the homes within the microgrid, considering predicted solar energy.

3.2 Solar Power optimal Distribution

Once the solar power is distributed based on the predicted solar energy, we can allocate the actual solar generation to each home proportionately. This ensures that each home receives a share of the actual solar generation based on its proportionate share of the predicted solar energy.

To calculate the fraction of predicted solar energy used by each home, denoted as f_i, we divide the distributed solar power x_i by the sum of all distributed solar power:

$$f_i = \frac{x_i}{\sum_{j=1}^{N} x_j}$$

Next, we distribute the actual solar generation G among the homes based on their proportionate share:

$$g_i = f_i \cdot G$$

This ensures that each home receives a fraction of the actual solar generation proportional to its allocated solar power. By considering the actual solar generation and adjusting the distribution accordingly, we optimize the utilization of solar power within the microgrid.

4 Experimental Set up

This section describes the experimental setup used to evaluate the proposed optimization-based solar power distribution technique. The experiments are conducted using Python programming language with the support of the Google Colab platform. We use the Gurobi optimization library for mathematical optimization problems.

4.1 Data Generation

We generate synthetic data for demand, predicted and actual solar generation to simulate the microgrid environment. The demand data is generated using a uniform distribution within a specified range, representing the varying energy requirements of homes in the microgrid.

4.2 Experimental Procedure

The experiments consist of two main scenarios: Simulation 1 focuses on energy waste reduction, while Simulation 2 investigates the impact of forecasting accuracy on energy waste.

For Simulation 1, we compare the energy waste achieved using the optimization-based approach against a baseline distribution method. The experiments are repeated multiple times with different demand and solar generation profiles to obtain statistically significant results.

For Simulation 2, we vary the accuracy levels of the solar energy forecasting model. The optimization-based approach is applied for each accuracy level, and the resulting energy waste is measured and compared. The experiments are repeated across different accuracy levels to establish a relationship between forecasting accuracy and energy waste reduction.

4.3 Evaluation Metrics

The performance of the optimization-based solar power distribution technique is being evaluated using the amount of unused or wasted energy within the microgrid. We calculate the energy waste by comparing the distributed power with the actual demand of each home.

5 Simulation Results

5.1 Simulation 1

We conduct extensive simulations using representative data and realistic scenarios to evaluate the effectiveness of our proposed optimization-based approach for solar power distribution in microgrids. Based on the solar power forecasts, our optimization framework dynamically allocates solar energy among homes within the microgrid to meet their energy demands while minimizing energy waste. Then the actual generated solar power has been distributed according to this allocation. We compare the performance of our optimization-based approach with a baseline scenario where solar power distribution is uniform, based solely on real-time solar generation without any optimization. The key performance metric energy waste is evaluated.

In the non-optimized method, the actual solar energy output is 26 units, evenly distributed among 10 houses (2.6 units per house). However, using the ILP-based optimization method, the predicted solar energy output is 28 units. The optimal distribution fractions are calculated based on this prediction to allocate the available solar energy among the houses, considering their individual energy demands. The goal is to minimize energy waste and meet the total demand of 32.05 units as closely as possible.

The simulation results shown in Table 2 demonstrates significant improvements achieved by our proposed approach, compared to the baseline scenario, whose result shown as Table 1, our optimization-based approaches led to a considerable increase in energy utilization, with a reduction in energy waste by up to almost 42%. This improvement is primarily attributed to the dynamic adjustments in power distribution based on the predicted solar energy, which effectively utilized the available solar resources.

Furthermore, our approach exhibits enhanced grid stability by ensuring a balanced solar power distribution among homes. The optimization framework intelligently manages the power allocation, considering factors such as energy demand and grid constraints. As a result, the microgrid experienced fewer power fluctuations and maintained a stable electricity supply to all homes. Overall, the simulation results validate the effectiveness of our proposed optimization-based approach for solar power distribution in microgrids.

5.2 Simulation 2

This simulation result demonstrates the relationship between accuracy level and energy waste in the solar power distribution system. In this context, accuracy

House Number	Demand	Solar Energy	Energy Waste
1	2.54	2.6	0.06
2	1.2	2.6	1.4
3	4.47	2.6	1.87
4	3.75	2.6	1.15
5	3.02	2.6	0.42
6	2.58	2.6	0.02
7	4.21	2.6	1.61
8	4.35	2.6	1.75
9	2.08	2.6	0.52
10	3.81	2.6	1.21
Total	32.05	26	10.01

Table 1. Unifrom distribution Strategy

House Number	Demand	Optimal Fraction	Solar Energy	Energy Waste
1	2.54	0.08	2.08	0.46
2	1.2	0.03	0.78	0.42
3	4.47	0.15	3.9	0.57
4	3.75	0.12	3.12	0.63
5	3.02	0.09	2.34	0.68
6	2.58	0.08	2.08	0.5
7	4.21	0.14	3.64	0.57
8	4.35	0.14	3.64	0.71
9	2.08	0.06	1.56	0.52
10	3.81	0.12	3.12	0.69
Total	32.05	1	26	5.75

Table 2. ILP-based distribution Strategy

refers to the measure of proximity between synthetically generated predicted solar power and the actual solar power value. The relationship between accuracy level and energy waste is illustrated in Figure 3. The plot depicts a decreasing trend, indicating that as the accuracy level increases from 0.6 to 1, the energy waste decreases. This trend highlights the importance of accurate solar power forecasting in optimizing solar power distribution and minimizing energy waste in microgrid systems.

A higher accuracy level implies the predicted solar energy closely aligns with the actual solar generation. Consequently, the distribution optimization model can allocate solar power more effectively, reducing energy waste.

6 Discussion

This section analyzes the impact of the optimization-based solar power distribution technique on energy waste reduction and the relationship between the accuracy of the forecasting model and energy waste.

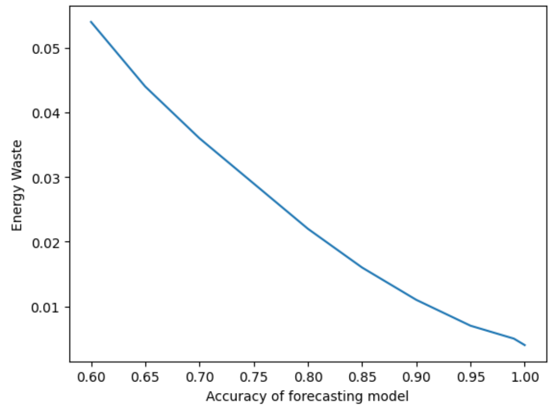

Fig. 3. Energy Waste vs. Accuracy Level

6.1 Impact of Optimization-Based Distribution

Simulation 1 focuses on evaluating the impact of the optimization-based distribution technique on energy waste reduction within the microgrid. The results demonstrate the effectiveness of our approach in minimizing energy waste.

By optimizing the distribution of solar power among homes based on their specific demand, we significantly reduce energy waste. The simulation results show a decrease in energy waste by 4.26 units in the case of the ILP-based optimization technique, which corresponds to a reduction of energy waste of more than 42% compared to the baseline distribution method.

The optimization model effectively balances the available solar energy with the demand of each home, ensuring that no excess power is distributed beyond the requirements. By considering the individual demand profiles and adapting the distribution accordingly, the optimization-based approach maximized the utilization of solar power resources, reducing waste.

The optimization-based distribution technique can be implemented in real-world microgrid systems to improve energy efficiency and reduce environmental impact.

6.2 Effect of Accuracy of Forecasting Model

Simulation 2 aims to investigate the relationship between the accuracy of the forecasting model and energy waste in the microgrid. By varying the accuracy levels of the forecasting model, we assess how the quality of solar energy predictions influences energy waste.

The results demonstrate a strong correlation between the accuracy of the forecasting model and energy waste reduction. As the accuracy of the forecasting model increased, the energy waste consistently decreased.

Improved accuracy in solar energy prediction enables more precise planning and distribution of solar power among homes. A more accurate forecast allows for better alignment between distributed power and solar generation. Consequently, the microgrid can optimize its energy distribution strategy and minimize waste.

7 Conclusion and Future Work

In conclusion, our research demonstrates the effectiveness of an optimization-based approach for solar power distribution in microgrids. By considering both predicted solar energy and actual solar generation, we reduce energy waste. The results clearly show that as the accuracy of the solar power forecasting model increased, the energy waste decreased significantly. This highlights the importance of accurate predictions in achieving energy efficiency. Future work can explore integrating additional factors and the scalability of the proposed approach. Overall, our research contributes to advancing solar microgrid optimization and provides practical insights for microgrid operators and energy management systems.

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