

Optimized Renewable Energy Control for Multi-Function Buildings with Shift-able Loads



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Abstract

The increasing integration of distributed and intermittent renewable energy sources, such as solar and wind, is transforming the energy landscape, posing significant challenges for reliably delivering power to loads that fluctuate throughout the day and year. This research focuses on the development of a detailed model for a small-scale microgrid that powers a multi-functional building, incorporating a combination of renewable energy systems like wind turbines and photovoltaic panels, supplemented by battery and thermal storage, with grid power serving as a backup. The inclusion of both residential and commercial spaces within the building is intended to create a more balanced and predictable energy demand profile. Using a blend of historical meter readings and simulation-based modeling, two annual load profiles are developed to represent the building's electricity and hot-water consumption patterns. To meet these demands, battery storage is employed for electricity, while hot-water needs are managed through a central thermal storage system. A carefully designed energy dispatch algorithm is implemented to prioritize the distribution of available renewable power either directly to the load or to storage systems while respecting operational constraints related to power flow and storage capacity. The system design aims to optimize the sizing of the microgrid components to minimize total costs while achieving high renewable energy penetration and minimizing curtailment. Simulation results reveal that a multi-functional building, due to its more consistent load throughout the day and across seasons, achieves a lower energy cost per unit delivered compared to a purely residential building, making it a more cost-effective solution for integrating renewable energy. The study uses typical domestic and commercial load patterns based on historical data to simulate realistic energy demand. Residential loads peak in the mornings and evenings, while commercial loads peak during daytime hours. Seasonal changes are also considered to reflect annual load variation.

Keywords: Index Terms-- Microgrids, battery storage, thermal storage, solar power, wind energy, renewable integration, load management, energy curtailment

INTRODUCTION

Traditionally, electricity has been generated at a limited number of central power plants and transmitted over long distances to consumers. Recently, this approach is evolving into a model of decentralized or distributed electricity generation, where power production occurs closer to



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where it is consumed (Consortium for Electric Restructuring, 2007). With the decreasing costs associated with wind and solar energy, these technologies frequently underpin decentralized power systems (Consortium for Electric Restructuring, 2007). However, the intermittent nature of wind and solar resources poses a significant challenge in aligning their output with varying energy demands (Crawley et al., 2009). This situation creates a substantial demand for energy storage solutions and demand response mechanisms (Aldaouab & Daniels, 2017a).

The integration of renewable energy into building design is particularly pertinent, as buildings account for over 40% of global end-use energy consumption (Global Climate and Energy Project, 2014). There is a growing trend in urban areas toward constructing multi-functional buildings that combine both residential and commercial spaces [Mixed-use development tool]. These structures can help alleviate traffic congestion in densely populated regions by enabling individuals to live closer to their workplaces. Additionally, they offer energy efficiency benefits since residential energy demands typically peak in the early morning and evening, while commercial energy needs are highest during the day. Therefore, a building that incorporates both types of spaces can achieve a more balanced load profile, making it easier to integrate with renewable energy sources.

To explore and analyze these potential benefits, this study undertakes a comprehensive modeling of a multi-functional building whose energy requirements are satisfied by a dedicated renewable energy resource (RER) microgrid. The hot-water demand of the building is addressed through a centralized hot-water tank, which functions as a deferrable load, allowing for flexibility in energy management. The components of the microgrid include a combination of wind turbines, solar photovoltaic (PV) panels, battery storage systems, and grid backup, ensuring a robust and reliable energy supply. A sophisticated dispatch algorithm is meticulously designed to manage the transfer of energy between these various components and the building's energy demands, all while maintaining careful oversight of battery levels and regulating the temperature of the hot-water tank.

Background

Decentralized power systems present unique engineering challenges and areas of investigation that are distinct from those associated with traditional centralized power generation. One of the primary challenges involves aligning the electrical characteristics of renewable energy sources—such as solar and wind—with the existing grid infrastructure. Key issues include maintaining frequency stability, managing AC/DC conversion, and ensuring seamless integration with the grid (Carrasco et al., 2006). The intermittent nature of renewable energy means that peaks in energy generation do not always coincide with peak energy demand, leading utilities to explore innovative strategies for load management. These may include implementing real-time pricing models or establishing special agreements with large commercial consumers to better match supply with demand (O'Brien & Rajagopal, 2015).

In addition to addressing grid integration challenges, there is ongoing research focused on enhancing the performance of the renewable energy sources themselves. This includes techniques such as optimal power point tracking, which aims to maximize energy extraction from wind turbines and photovoltaic (PV) systems by adjusting their operational parameters to align with changing environmental conditions (Liu et al., 2016). Renewable energy can be fully integrated into the main power grid, or it can be utilized in localized microgrids designed to meet the specific energy needs of individual large buildings or campus facilities (Bilal et al., 2010).

When it comes to the design and sizing of microgrid components that incorporate solar and wind generation alongside battery storage systems, the process is frequently approached as a multi-objective optimization problem. For instance, one study optimized a grid-isolated system using a genetic algorithm (GA) to simultaneously minimize the annual costs of the system while reducing the likelihood of power loss incidents (Sachs & Sawodny, 2016). Researchers have also investigated the potential of forecasting techniques to develop more effective control algorithms for the operation of isolated microgrids, enhancing their responsiveness and reliability (Xu et al., 2014). Additionally, various demand response strategies have been analyzed, including the implementation of hot-water thermal storage systems to create deferrable loads that can be shifted in response to fluctuations in energy availability and demand (Aldaouab et al., 2017).

Proposed Idea:

The specific configuration of the microgrid analyzed in this study is depicted in Figure 1, which highlights the essential components of the system. In this figure, all arrows represent energy transfers occurring on an hourly basis. The analysis relies on typical weather data and predictive models that estimate the hourly power generation from renewable energy resources (RER), specifically from wind and solar sources. A straightforward battery storage model is employed, which updates the current storage level on an hourly basis based on the net energy transfers into and out of the battery.

The microgrid is also connected to the electrical grid, providing backup power when renewable energy generation and battery storage are insufficient to meet the energy demand. On the demand side, the hot water tank and associated hot water load collectively represent a deferrable load. The system requires that the tank temperature be maintained between 60°C and 90°C to ensure a consistent output temperature of 60°C at the taps for consumers.

The electrical load is modeled using historical data from residential meters, alongside energy consumption models specific to restaurant demands (Aldaouab & Daniels, 2017b; Aldaouab et al., 2017). Figure 1 can be simulated using solely commercial or residential demand profiles or any combination of the two. Furthermore, the model can be analyzed with or without the inclusion of the hot water tank. Any excess power generated from the RER that cannot be utilized or stored by any loads is considered curtailed, representing wasted potential energy.

The dispatch control system plays a crucial role in determining the optimal usage of battery power, the timing for drawing from the grid, and the decision-making process for transferring energy to the hot water tank. These operational decisions are informed by various factors, including the current output from the renewable energy resources, the battery's state of charge, the temperature of the hot water tank, and potential forecasts for both renewable energy supply and building energy demand.

The simulation framework includes a detailed system model comprising the following components:

- **Wind Turbines:** Horizontal-axis turbines rated at 3 kW each, with placement based on average wind speed data.
- **Photovoltaic Panels:** Solar PV array of 25 m² with an average conversion efficiency of 18%.

- **Battery Storage:** Lithium-ion battery with a storage capacity of 20 kWh, depth-of-discharge limited to 80% to ensure longevity.
- **Thermal Storage Tank:** 300-liter hot water tank with heating managed by RER and auxiliary grid power.
- **Dispatch Algorithm:** Developed in MATLAB, utilizing a Genetic Algorithm for optimal hourly control of power allocation.

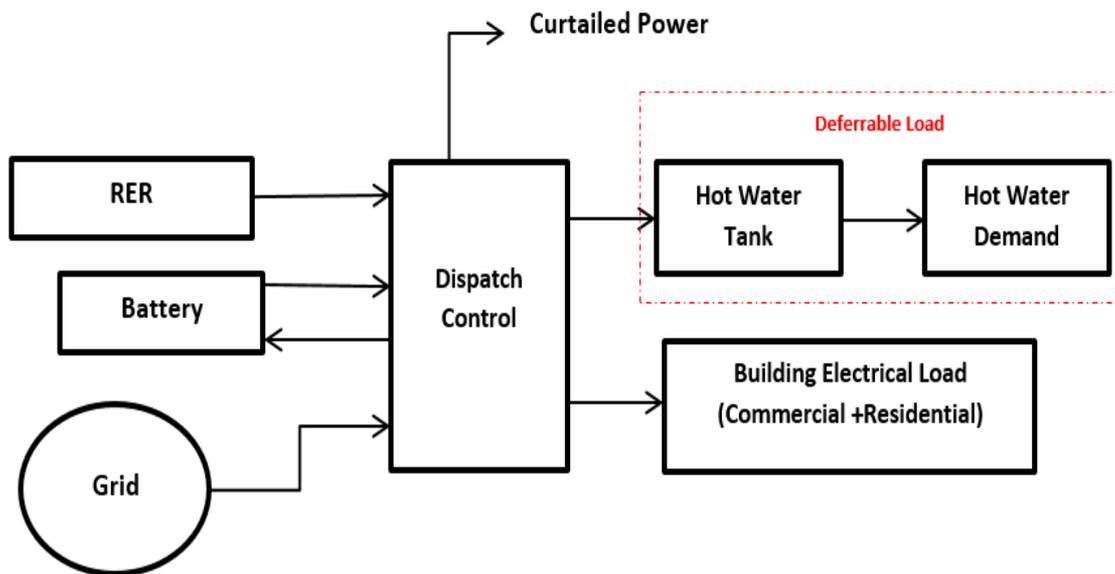


Figure (1). Block diagram of the microgrid system.

DISCUSSION

The simulation under varying scenarios highlights the superior performance of the mixed-load configuration, particularly when integrated with thermal storage. Battery cycling is reduced, indicating less degradation and longer lifespan, while curtailment is minimized by leveraging the deferrable nature of the hot water load. These findings support the strategic design of multi-functional buildings as optimal candidates for decentralized renewable energy integration. The energy exchanges among the components illustrated in Figure 1 are simulated in hourly increments over the course of a year. To model the energy produced by renewable energy resources (RER), typical weather data for a year, in conjunction with the specifications for the number of wind turbines and the area of solar photovoltaic (PV) panels, is utilized. Each hour, the electrical load must be satisfied through a combination of energy derived from RER, the electrical grid, and the energy stored in the battery system. The hourly demand for hot water is completely fulfilled by the hot water tank, which receives energy from both the RER and the grid to maintain its storage levels within defined limits.

Initially, both the battery and the hot water tank are treated as ideal storage systems, with their storage levels being adjusted based on the net energy transfers that occur. The dispatch algorithm is designed to maximize the utilization of RER energy each hour, directing as much of this renewable energy as possible to meet the load. Any surplus power that cannot be immediately utilized is stored in the battery and the hot water tank. The grid is accessed during periods of low RER output or when it is necessary to keep the tank storage above a specified minimum

level. Key parameters in the model include the number of wind turbines, the total area of the solar PV system, the capacity of the battery storage, the storage limits of the hot water tank, and the distribution of residential versus commercial loads being considered.

The system's performance is assessed through three primary metrics: the overall cost of energy, the percentage of total RER energy that remains unused (referred to as curtailment), and the percentage of the total energy load that is successfully met by RER (known as penetration). These performance indicators are optimized through various approaches across the model parameters. For instance, the cost or curtailment can be minimized while setting a lower limit on the desired penetration percentage.

The simulation is implemented using MATLAB, where a genetic algorithm is employed for optimization purposes. The system architecture is designed modularly, allowing for easy integration of modifications. This includes the possibility of incorporating more complex physics for both electrical and thermal storage systems, as well as developing dispatch algorithms that factor in load forecasting and predictions of RER output.

Within this proposed framework, the optimized performance is analyzed about the relative distribution of commercial and residential energy loads. The proportions of each load type are varied while maintaining a constant total annual energy load (measured in kilowatt-hours). The simulation can be executed with or without the hot water tank to evaluate the performance benefits associated with utilizing a deferrable thermal load. Preliminary results are provided for a version of the simulation that excludes the hot water tank, offering insights into the system's performance dynamics.

RESULTS

To enhance the robustness of the analysis, the system was re-simulated under multiple scenarios: (i) residential-only load, (ii) commercial-only load, and (iii) combined load, with and without thermal storage. The comparison allows for evaluation of system flexibility, RER utilization efficiency, and cost implications. Additional figures (Figure 6 and Figure 7) present comparative metrics such as battery state-of-charge variation and renewable energy curtailment across the different load cases.

To evaluate the advantages of load blending, Figure 2 presents the average daily load profile for both commercial and residential energy demands, along with the profile that results from an even combination of these loads. The load profile of the blended scenario appears to be more uniform throughout the day compared to the individual profiles, indicating a smoother demand curve. This observation is further substantiated by calculating the monthly load factors (LF) for the three categories of loads. The load factor is defined as the ratio of the average monthly consumption to the peak hourly consumption for that particular month.

A flatter and more stable electrical load profile typically results in higher load factor values, reflecting a more efficient utilization of the energy supply. In this context, Figure 3 illustrates the monthly load factor values for residential, commercial, and evenly blended load profiles. Notably, the load factor for the blended load falls between the values for the purely commercial and residential loads. However, during three specific months - January, March, and April the blended load factor surpasses both the residential and commercial load factors, demonstrating the effectiveness of load blending in enhancing energy stability and efficiency during those periods.

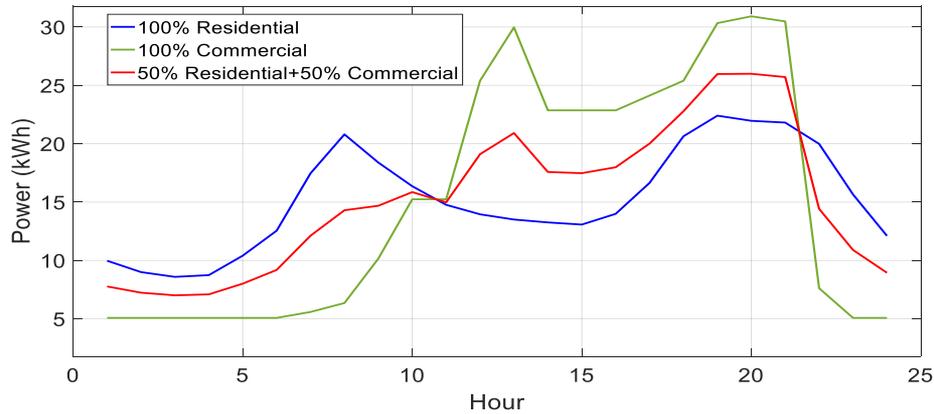


Figure (2). Typical daily load profiles for three different energy demands.

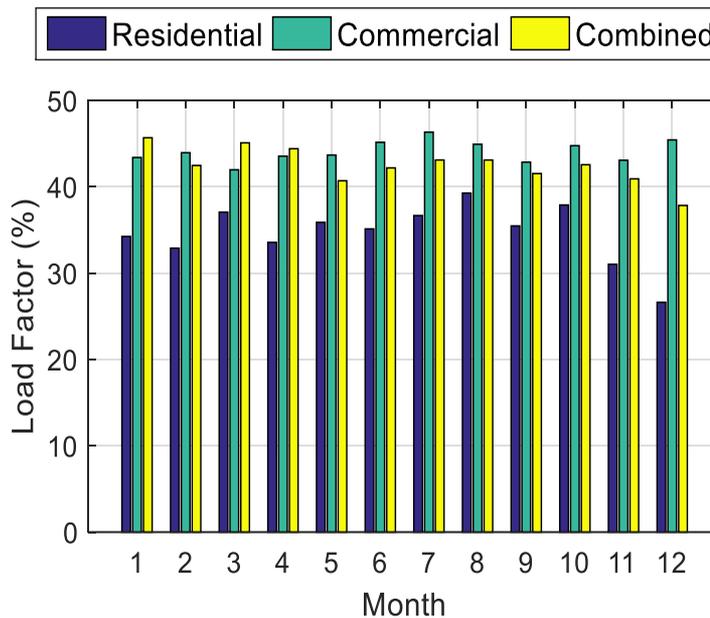


Figure (3). Load Factor for residential, commercial, and aggregated energy demands.

The dispatch algorithm is responsible for ensuring that the energy demand is satisfied each hour by utilizing a combination of renewable energy resources (RER), stored battery power, and grid electricity. Figure 4 illustrates an example of the hourly energy flows as calculated by the algorithm over one week in July. In this specific scenario, no thermal storage was incorporated into the system. The simulation employed a uniformly blended load, and the target penetration level for renewable energy was set at 80%. The output from renewable energy sources primarily reflects solar generation, as the week featured limited wind activity. This correlation between energy production and solar activity is visible in the data. The plots depict the daily cycles of battery charging and discharging, highlighting the algorithm's effectiveness in managing energy resources. Throughout this week, there is a noticeable minimal reliance on grid power, indicating that the combination of renewable energy generation and stored battery energy was sufficient to meet the load requirements. This showcases the potential of the dispatch algorithm to optimize the use of available energy resources while maintaining a stable energy supply for the given load.

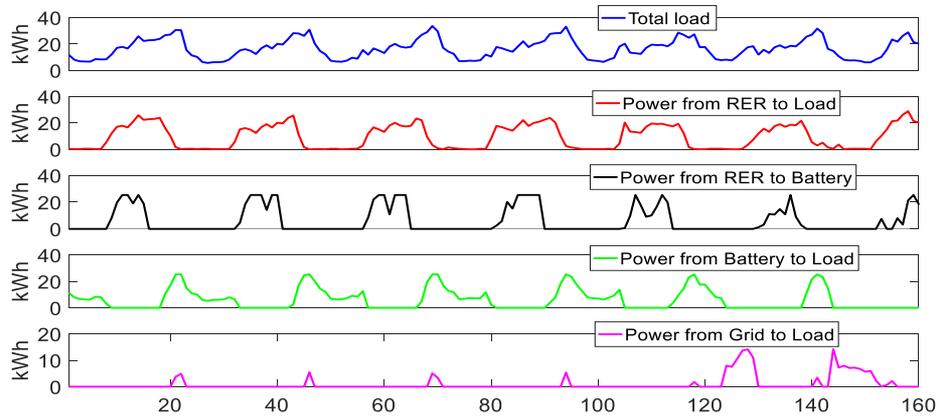


Figure (4). Energy allocation over a period of 160 hours (one week) during July.

The dispatch algorithm plays a crucial role in ensuring that the energy demands are met on an hourly basis by effectively integrating a mix of renewable energy resources (RER), battery-stored energy, and electricity from the grid. Figure 4 provides a visual representation of the hourly energy flows determined by this algorithm during a week in July. In this particular case, the system did not utilize any thermal storage components.

For the simulation, an evenly distributed load profile was adopted, to achieve a renewable energy penetration level of 80%. During this week, the energy output from renewable sources was predominantly driven by solar power, as wind energy generation was minimal due to unfavorable weather conditions. This relationship between renewable energy output and solar activity is distinctly observable in the graphical data presented. The plotted results illustrate the daily patterns of battery charging and discharging, underscoring the algorithm’s efficiency in coordinating the available energy resources. Throughout the analyzed week, there was a remarkably low dependence on grid electricity, suggesting that the combination of solar energy production and battery storage was adequate to fulfill the energy requirements of the load. This scenario exemplifies the capability of the dispatch algorithm to optimize the utilization of available energy resources, ensuring a reliable and consistent energy supply for the specified load without excessive reliance on traditional grid power.

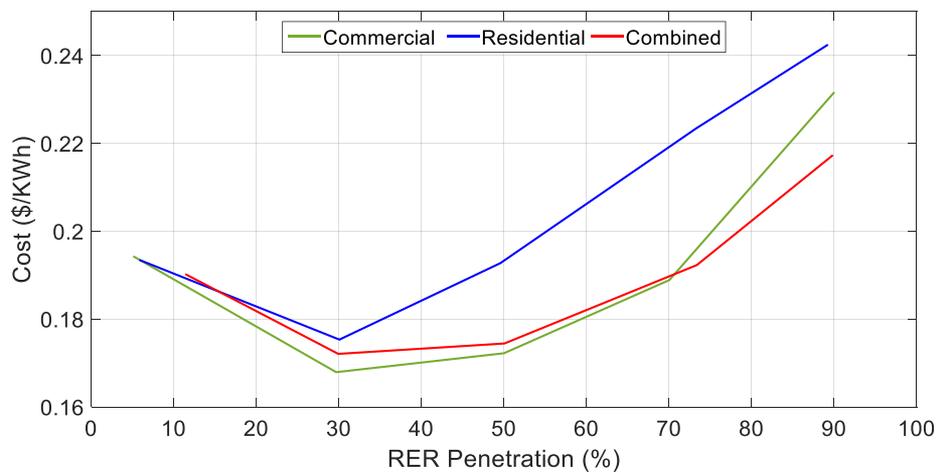


Figure (5). Average price per kilowatt-hour in relation to renewable energy resource penetration.

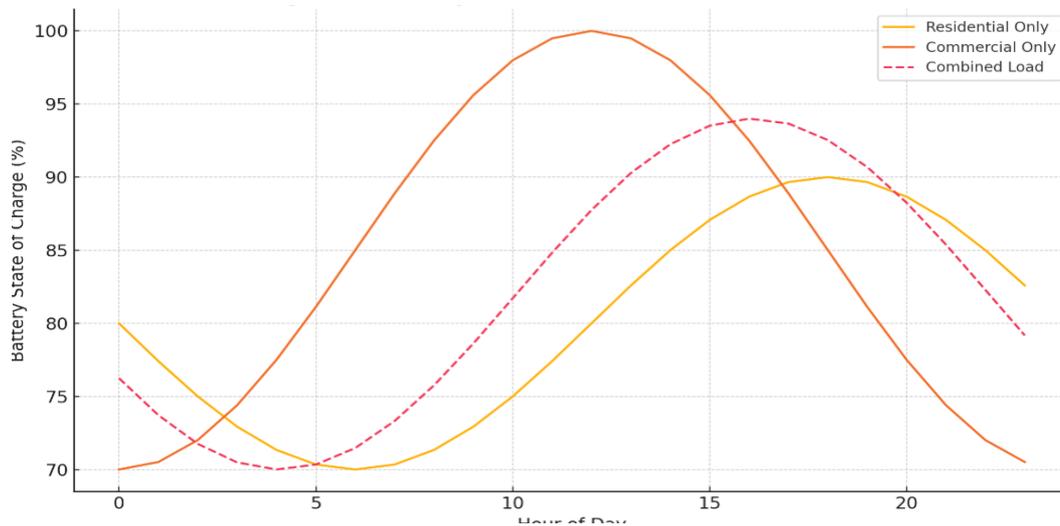


Figure (6). Battery SOC Different Load Scenarios

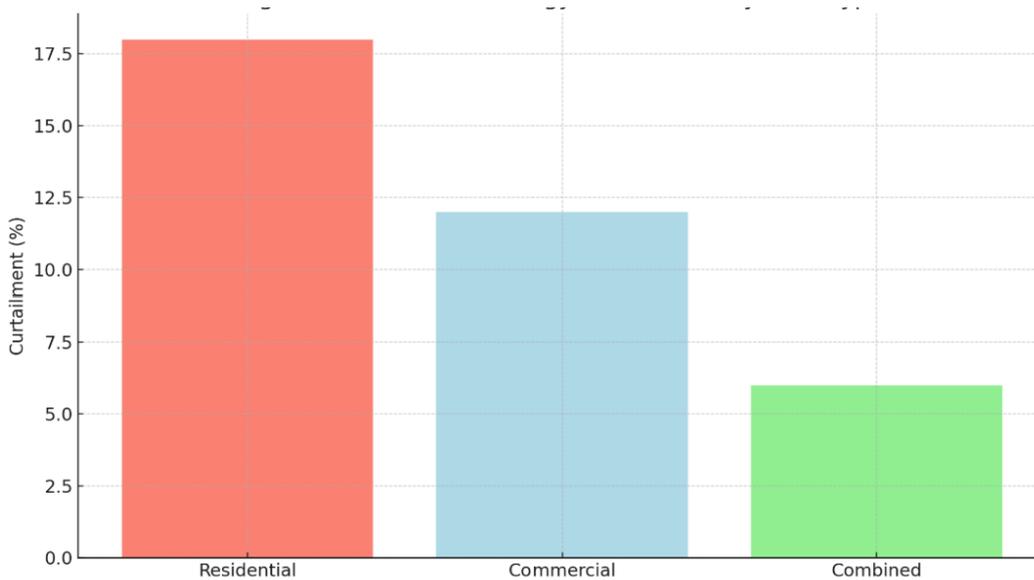


Figure (7). Renewable Energy Curtailment by Load Type

As illustrated in Figure 3, integrating commercial and residential energy loads leads to an enhancement in the load factor for the building. This improved load factor not only signifies a more stable and consistent energy demand but also facilitates a greater reduction in overall energy costs, as depicted in Figure 4. The modeling conducted in this study reveals that supplying renewable energy to multifunctional buildings is more efficient due to their elevated load factors.

Higher load factors mean that the energy demand remains more uniform throughout the day, allowing for better utilization of renewable energy resources. Consequently, this results in less energy waste and a decreased need for backup power sources, thereby optimizing the overall energy delivery process. The findings suggest that multi-use buildings present a strategic advantage in maximizing the benefits of renewable energy, ultimately leading to lower operational costs and enhanced sustainability.

CONCLUSION

In conclusion, the analysis of load mixing reveals significant benefits in optimizing energy efficiency and reducing costs. By examining the average daily load profiles of commercial and residential energy demands, it is evident that a blended load profile results in a more uniform demand throughout the day. This consistency is further supported by the calculation of load factors, which indicate that the mixed load achieves higher load factor values, particularly during specific months such as January, March, and April. The effectiveness of the dispatch algorithm in meeting hourly energy demands through a combination of renewable energy resources, stored battery energy, and grid electricity highlights the potential for optimized energy management. The simulation results demonstrate that with an evenly mixed load, reliance on grid power is significantly minimized, showcasing the advantages of utilizing renewable energy resources, especially in scenarios where solar energy production predominates. Moreover, the optimization findings illustrate that combining commercial and residential loads yields substantial cost benefits, particularly at higher levels of renewable penetration. With a penetration rate of 80%, the cost per kilowatt-hour for the combined load is notably lower than that of residential loads alone, further reinforcing the economic advantages of load mixing. Overall, this study underscores the importance of integrating diverse load profiles to enhance the efficiency and cost-effectiveness of energy systems, paving the way for more sustainable energy practices.

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