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Hybrid Intelligent Control System for Adaptive Microgrid Optimization: Integration of Rule-Based Control and Deep Learning Techniques

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Abstract: Microgrids (MGs) have evolved as critical components of modern energy distribution networks, providing increased dependability, efficiency, and sustainability. Effective control strategies are essential for optimizing MG operation and maintaining stability in the face of changing environmental and load conditions. Traditional rule-based control systems are extensively used due to their interpretability and simplicity. However, these strategies frequently lack the flexibility for complex and changing system dynamics. This paper provides a novel method called hybrid intelligent control for adaptive MG that integrates basic rule-based control and deep learning techniques, including gated recurrent units (GRUs), basic recurrent neural networks (RNNs), and long short-term memory (LSTM). The main target of this hybrid approach is to improve MG management performance by combining the strengths of basic rule-based systems and deep learning techniques. These deep learning techniques readily enhance and adapt control decisions based on historical data and domain-specific rules, leading to increasing system efficiency, stability, and resilience in adaptive MG. Our results show that the proposed method optimizes MG operation, especially under demanding conditions such as variable renewable energy supply and unanticipated load fluctuations. This study investigates special RNN architectures and hyperparameter optimization techniques with the aim of predicting power consumption and generation within the adaptive MG system. Our promising results show the highest-performing models indicating high accuracy and efficiency in power prediction. The finest-performing model accomplishes an R^2 value close to 1, representing a strong correlation between predicted and actual power values. Specifically, the best model achieved an R^2 value of 0.999809, an MSE of 0.000002, and an MAE of 0.000831.

Keywords: deep learning; energy management system; optimization; microgrid; resilience; rule-based control; stability



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1. Introduction

Since microgrid (MG) systems can increase sustainability, efficiency, and dependability, they have become vital parts of modern energy distribution networks [1,2]. Renewable energy sources (RESs), energy storage devices, and controlled loads are combined in these distributed energy systems to enable them to operate either independently or in conjunction with the main grid [3,4]. Optimizing MG operation, maintaining stability, and using renewable resources most depend on effective control strategies [5–7]. Because they are straightforward and clear, traditional rule-based control techniques have been

extensively employed in MG management systems. Nevertheless, these techniques often have difficulty adjusting to dynamic and uncertain operating conditions, which restricts their use in maximizing system performance [8–10].

To solve these problems and create hybrid control systems for MG management, there is growing interest in merging rule-based control methodologies with deep learning techniques [11]. In order to enable more adaptive and clever control decisions, deep learning models with the ability to comprehend intricate patterns and relationships from historical data include gated recurrent units (GRUs), long short-term memory (LSTM), and recurrent neural networks (RNNs) [12]. Hybrid control approaches can potentially improve machine learning systems' efficiency, stability, and resilience by fusing the interpretability of rule-based systems with the learning power of deep neural networks [13].

In this study, we introduce a novel strategy that combines deep learning technology with rule-based control to optimize MG operation. We thoroughly investigate the hybrid approach's performance against both classic deep learning approaches and independent rule-based control using simulated machine learning circumstances. The findings demonstrate that the proposed strategy enhances MG performance across various environmental factors and load dynamics. This work improves the field of adaptive MG control by introducing a novel framework that combines the advantages of rule-based control and deep learning techniques.

1.1. Literature Review

Several authors have used stochastic dynamic programming and optimization methods in their studies, including [14–18]. To reduce distribution network losses, various research studies have employed the cuckoo search (CS) algorithm and the grasshopper optimization algorithm (GOA) to optimize the operation of RESs [19]. Ref. [20] uses distributed proximal primal–dual (PD) to manage distributed energy with flexible loads and distributed generators with transmission losses. They describe a PD-based distributed algorithm with dynamic weights that allocates diverse energy sources for efficient energy management while maintaining tolerable operational costs and gas emissions. This approach is less computationally complex than distributed optimization algorithms [21]. In addition, Refs. [22,23] investigated using model predictive control (MPC) to manage hybrid MG systems. In Refs. [24–26], the combination of switched MPC (S-MPC) and ϵ -variables, called enhanced optimal ϵ -variables, has been employed for improving the adaptability and scalability of the MG control. In [27], the teaching learning-based optimization (TLBO) method was applied to solve a multi-objective optimization problem, reducing costs and improving the reliability of the MG. They discovered that charging and discharging energy storage systems (ESSs) reduce MG expenses while improving system performance and reliability. In [28,29], simulation findings demonstrate the effectiveness of the master–slave (MS) peer-to-peer integration microgrid control method based on communication in achieving stable operation of the MG in grid-connected and islanded states and smooth switching between these two modes. Finally, Ref. [30] used the particle swarm optimization (PSO) approach to develop a hybrid renewable energy system (HRES) that comprises PVs, wind turbines, and battery units while minimizing the overall cost.

RNNs have been widely applied in time-series prediction tasks due to their ability to capture temporal dependencies within sequential data. Refs. [31,32] applied RNNs to predict RESs generation and MG load demand, demonstrating the effectiveness of this approach in achieving accurate predictions. LSTM networks, a variant of RNNs, have been extensively utilized in energy management systems due to their capability to effectively capture long-term dependencies and handle vanishing or exploding gradient problems. Refs. [33–35] introduced an LSTM-based energy management system for MGs, achieving superior performance in predicting power consumption and generation and enhancing the stability and reliability of the MG. GRUs have gained attention in recent years due to their simpler architecture and efficiency in training. Refs. [36–38] proposed a hybrid deep

learning approach integrating GRUs into MG control, enhancing system efficiency and adaptability under dynamic conditions.

This research employs a rule-based system to manage diverse energy resources and demand responses on the load side. The major goal was to optimize energy utilization and save energy while considering adaptive MG operational costs. The rule-based method has demonstrated promising results in numerous applications [39], including grid-based energy management systems (EMSs), RESs, and battery energy resources. It is also employed in the switching procedure of the EMS strategy in train applications [40]. The rule-based approach is appropriate for deciding the operating strategy of equipment in an energy system during a day, month, or year based on stated and pre-determined rules [41]. Numerous research studies have focused on applying rule-based control strategies to MG management. Rule-based control operates MG components, including loads, ESSs, and renewable energy generators, using predefined logic and decision-making rules. Although rule-based plans are straightforward to understand and implement, they may not efficiently use the resources at hand and are frequently not flexible enough to react to changing operating situations [42].

Deep learning algorithms can improve MG management by identifying implicit patterns and linkages from prior data [43–45]. GRUs and LSTM are two popular deep-learning architectures that excel in detecting sequential patterns and temporal relationships in time-series data. Training deep learning models on historical data leads to more precise predictions and control decisions, improving MG performance [46–48].

In recent years, there has been considerable emphasis on building hybrid control systems for MG management by combining deep learning methods with rule-based control [49–52]. These hybrid approaches aim to integrate rule-based systems' interpretability with deep neural network learning capabilities to provide more flexible and intelligent control techniques. Hybrid control systems can improve MG operation efficiency, stability, and resilience by applying domain-specific rules and historical data [53–55].

Table 1 compares various control and optimization methods for adaptive microgrids. Rule-based control methods show strong optimization but lack prediction, rendering them weak and unstable. MPC offers optimization but exhibits weakness in flexibility. ϵ -variables demonstrate strong flexibility but lack both optimization and prediction capabilities, rendering them as having weak instability. The GOA and CS show weaknesses in all aspects except for stability, which is moderate. The PSO presents moderate flexibility but fails in prediction, while the TLBO indicates moderate flexibility but with weak prediction and optimization capabilities. LSTM and GRU models offer moderate optimization and flexibility, with LSTM showing strong performance in prediction and stability. Our proposed hybrid intelligent control outperforms all other methods across optimization, flexibility, prediction, and stability, making it an efficient solution for energy management within adaptive MG systems.

Table 1. Comparison of various control and optimization methods for adaptive MGs.

Methods	Optimization	Flexibility	Prediction	Stability	Ref.
Rule-based control	✓	Strong	X	Weak	[11,49]
MPC	✓	Weak	Moderate	Moderate	[24–26]
ϵ -variables	X	Strong	X	Weak	[4,22]
GOA	✓	Weak	Weak	Moderate	[19]
PSO	✓	Moderate	X	Weak	[30]
TLBO	✓	Moderate	Weak	Moderate	[27]
LSTM	✓	Moderate	Strong	Strong	[33–35]
GRU	✓	Moderate	Moderate	Moderate	[37,38]
Hybrid intelligent control	✓	Strong	Strong	Strong	Our paper

In this paper, we build on previous studies by providing a novel method for optimizing MG operation that combines deep learning approaches such as GRUs, LSTM, and RNNs with rule-based control. Using simulated MG circumstances, we comprehensively compare the performance of the hybrid approach to standalone rule-based control and traditional deep learning techniques. The findings highlight the potential of hybrid control systems for future MG management applications and demonstrate how well the proposed technique works to improve MG performance under various environments and load conditions.

1.2. Contributions

- **Novel Method for Integrating Control and Deep Learning Methods:** Developing a proposed method known as a hybrid intelligent control method for adaptive MG optimization is an innovative way to integrate cutting-edge deep learning algorithms with basic rule-based control approaches. This unique approach combines deep neural network learning with rule-based logic interpretability to provide a complete solution for optimizing adaptive MG operations.
- **Enhanced Flexibility (Adaptability) and Intelligence:** The hybrid intelligent control method greatly increases the flexibility and intelligence of MG control systems. Using deep learning algorithms such as GRUs, LSTM, and RNNs, the system can learn complex patterns and correlations from past data, allowing for more informed and dynamic control decisions in real time.
- **Improved Efficiency and Performance:** The proposed method's integration of deep learning techniques enhances the effectiveness and performance of MG operations. The system maximizes the environmental advantages of MG deployment by maximizing the utilization of RESs, minimizing peak demand, and improving overall system stability and resilience through optimizing EMSs.

2. Materials and Methods

2.1. Rule-Based Control

Figure 1 represents the adaptive MG structure controlled in this paper. The MG is composed of a photovoltaic (PV), grid (GR), ESS, load (LD), electrolyzer (EL), and fuel cell (FC). The ESS is composed of a battery (BAT), fuel tank (FT), and water tank (WT). The PV can be used as the primary energy source for the MG. If the PV cannot generate adequate power, the ESS will ensure that the load is met. If the ESS is depleted and no hydrogen is available, the GR will supply the energy. When the ESS is full, and there is a surplus, the EL is employed if there is space in both the WT and the FT. The energy will then be delivered to the GR. The MG's ESS reduces peak demand from a cluster of loads in the distribution network [56]. P_{LD} stands for the total demand of these loads, while P_N represents the power obtained from the upstream network, constrained by the network operator's set boundaries (P_N^{max}). The symbols η_{ch} and η_{dis} denote the efficiency of the ESS during the charging and discharging phases, respectively. C represents the nominal capacity of the ESS, expressed in kWh. $P_{ESS}(k)$ denotes the power exchanged with the network during the current operational time. A positive value of $P_{ESS}(k)$ indicates the charging state, while a negative value indicates the discharging state. The state of charge (SOC) during the current operational period (k) is determined by the energy exchanged through the ESS and its value from the previous period ($k - 1$).

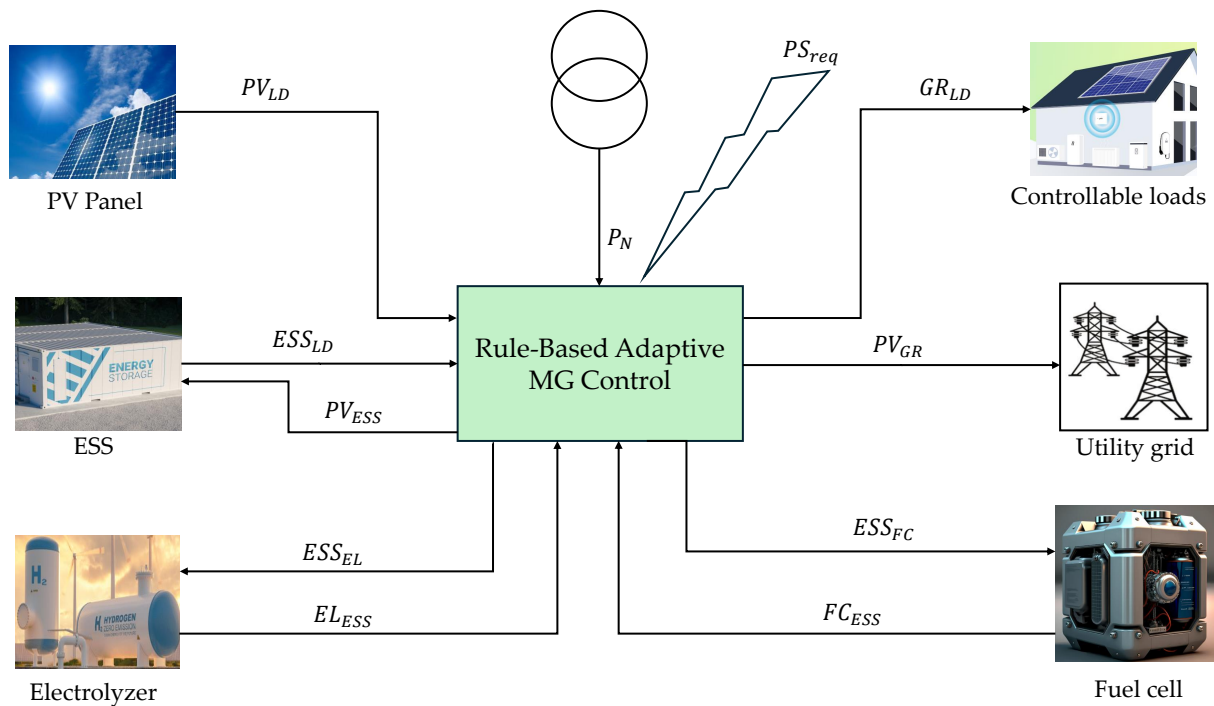


Figure 1. The adaptive MG structure.

The rule-based EMS controls the ESS, which uses the measured values of P_{LD} and P_{ESS} to establish the proper set-point for power exchange. Figure 2's flow chart shows this EMS, emphasizing the importance of SOC as a critical parameter for sending control commands. Utilizing the following relationships, the SOC of the ESS during the current operational period (k) is determined by the energy exchanged through the ESS. It is calculated using the following equations:

$$SOC(k) = \begin{cases} SOC(k-1) + \left(\frac{P_{ESS}(k) \cdot \eta_{ch} \cdot k}{C} \right) & \text{if } P_{ESS}(k) > 0 \\ SOC(k-1) + \left(\frac{P_{ESS}(k) \cdot k}{C \cdot \eta_{dis}} \right) & \text{if } P_{ESS}(k) < 0 \end{cases} \quad (1)$$

The equations represent the SOC of ESS at the time step k . In the first case of Equation (1), if the power flowing into the ESS ($P_{ESS}(k)$) is positive, it means that the battery is charging, and the SOC is updated using the charging efficiency η_{ch} . On the other hand, in the second case of Equation (1), if the power flowing into the ESS ($P_{ESS}(k)$) is negative, it means that the battery is discharging, and the SOC is updated using the discharging efficiency η_{dis} .

The illustrated EMS has an hourly control horizon and weekly operational periods (k), which need the EMS to take the necessary control actions. By maintaining a 50% SOC at the end of the control horizon, the ESS will have enough energy reserves to provide peak reduction in the following days. It is considered that the distribution network's chosen location for peak reduction services, with an SOC ranging from 20% to 100%, has an ESS that is optimally sized to support it. The purpose of setting the bottom boundary of the SOC is to guarantee that the ESS runs smoothly. In order to ensure effective operation and peak demand mitigation, the rule-based EMS uses measured values of P_{ESS} and P_{LD} to calculate the optimal power exchange set-point for the ESS.

Furthermore, since the main goal is to determine the best imputation technique for missing data within the ESS, it is assumed that there are no missing values in P_{LD} .

The control decisions of the adaptive MG are defined to find the optimum system control, state, and output vectors for the rule-based control.

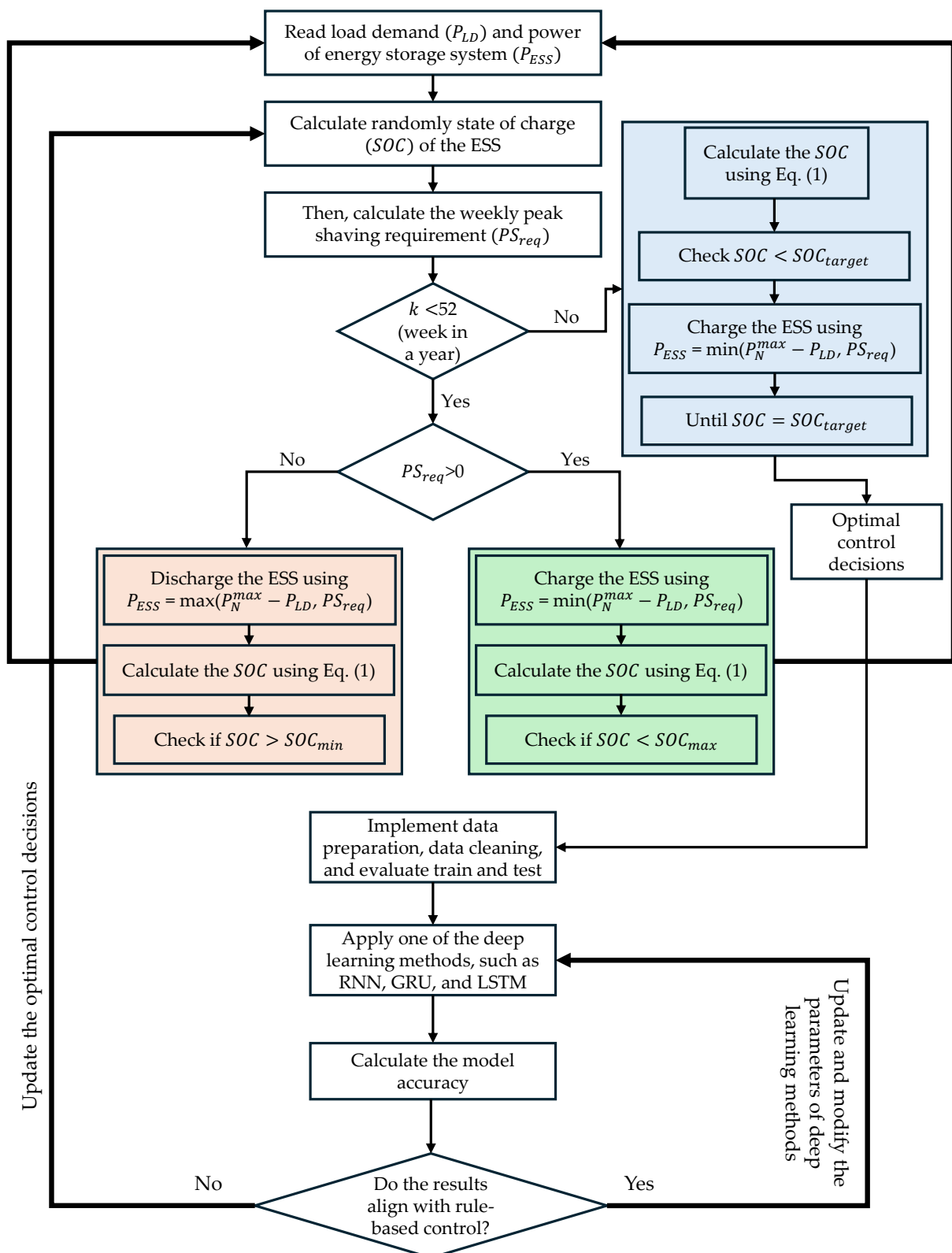


Figure 2. Flow chart of hybrid intelligent control method for adaptive MG optimization (blue colour: calculation of SOC, green colour: charging of SOC of the ESS and pink colour: discharging of SOC of the ESS).

Define the adaptive MG's system state, control, and output vectors with the help of Equation (1):

$$x(k) = [SOC^{ESS}(k)] \quad (2)$$

where $SOAcc^{ESS}(k)$ is the state of charge for the ESS.

The system control (input) vector of the adaptive MG is defined as follows [26]:

$$u(k) = [PV_{LD}(k); PV_{GR}(k); PV_{ESS}(k); ESS_{LD}(k)] \quad (3)$$

where PV_{LD} , PV_{GR} , and PV_{ESS} are the power flow from the PV to the LD, GR, and ESS, respectively. ESS_{LD} is the power flow from the ESS to the LD. In this case, the ESS is in discharge mode.

The system output vector of the adaptive MG is as follows:

$$y(k) = [GR_{LD}(k); ESS_{GR}(k)] \quad (4)$$

where GR_{LD} is the power import from the GR for the LD and ESS_{GR} is the power flow from the ESS to the GR.

Define the objective functions for the rule-based control on the adaptive MG [25]:

1. The power imported from the utility grid is minimized.

$$\min J_1(k) = \min \sum_k^{k+N_c} (P_{LD}(k) - (PV_{GR}(k) + ESS_{GR}(k) + GR_{LD}(k)))^2 \quad (5)$$

2. The usage of the ESS is penalized to prevent the charging from the utility grid.

$$\min J_2(k) = \min \sum_k^{k+N_c} (PV_{ESS}(k) - (ESS_{LD}(k) + ESS_{GR}(k)))^2 \quad (6)$$

3. The exported energy to the utility grid is encouraged.

$$\min J_3(k) = \min \sum_k^{k+N_c} (P_{PV}(k) - (PV_{ESS}(k) + PV_{GR}(k)))^2 \quad (7)$$

By merging Equations (5)–(7), the overall cost function (objective function) for the adaptive MG is as follows:

$$\min J(k) = \min (J_1(k) + J_2(k) + J_3(k)) \quad (8)$$

Define the constraints for the adaptive MG are as follows:

Power flows from the PV, GR, and ESS are non-negative values and are subject to their maximum values.

$$\begin{aligned} 0 &\leq PV_{LD}(k) \leq PV_{LD}^{\max} \\ 0 &\leq PV_{GR}(k) \leq PV_{GR}^{\max} \\ 0 &\leq PV_{ESS}(k) \leq PV_{ESS}^{\max} \\ 0 &\leq GR_{LD}(k) \leq GR_{LD}^{\max} \\ 0 &\leq ESS_{GR}(k) \leq ESS_{GR}^{\max} \\ 0 &\leq ESS_{LD}(k) \leq ESS_{LD}^{\max} \end{aligned} \quad (9)$$

The sum of the PV energy supplied directly for the LD (PV_{LD}), the ESS for the charging (PV_{ESS}), and the energy exported to the GR (PV_{GR}) should be smaller than the energy flow from the PV array, ($P_{PV}(k)$).

$$PV_{LD}(k) + PV_{ESS}(k) + PV_{GR}(k) \leq P_{PV}(k) \quad (10)$$

Also, the sum of the LD from the PV and ESS should equal the building's load demand.

$$PV_{LD}(k) + ESS_{LD}(k) + GR_{LD}(k) \leq P_{LD}(k) \quad (11)$$

The $SOAcc^{ESS}$ for the ESS is restricted between its minimum and maximum values.

$$SOAcc^{ESS^{min}} \leq SOAcc^{ESS} \leq SOAcc^{ESS^{max}} \quad (12)$$

Charging and discharging for the ESS cannot happen simultaneously, as is implied by the following:

$$\begin{aligned} PV_{ESS}(k)ESS_{LD}(k) &\leq 0 \\ PV_{ESS}(k)ESS_{GR}(k) &\leq 0 \end{aligned} \quad (13)$$

It is worth noting that Equations (9)–(12) are convex, whereas Equation (13) is non-convex. In order to accomplish convex optimization in rule-based control design, the non-convex constraints are separated into two switched cases: (i) charging ($ESS_{LD} = 0$ and $ESS_{GR} = 0$) and (ii) discharging ($PV_{ESS} = 0$).

1. Charging: The constraint can be re-written by [26]

$$\begin{aligned} ESS_{LD}(k) &\leq 0 \quad ESS_{LD}(k) \geq 0 \\ ESS_{GR}(k) &\leq 0 \quad ESS_{GR}(k) \geq 0 \end{aligned} \quad (14)$$

Constraints (9)–(11) and (14) can be compactly re-written by [26]:

$$\mu_{ch}u(k) \leq \gamma_{ch} \quad (15)$$

where

$$\mu_{ch} = \begin{bmatrix} 0 & 0 & 0 & -eye(6) & 0 & 0 \\ 1 & 1 & 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 1 & 0 & 0 \\ & & & eye(6) & & \\ -1 & -1 & 0 & 0 & 0 & -1 \end{bmatrix} \quad \gamma_{ch} = \begin{bmatrix} zeros(6,1) \\ 0 \\ P_{LD}(k) \\ P_{PV}(k) \\ P_m^{max}ones(6,1) \\ PV_{GR}^{max} - P_{LD}(k) \end{bmatrix} \quad (16)$$

where eye is an identity matrix, and $zeros$ is creating an array of all zeros.

2. Discharging: The constraint can be re-written by

$$PV_{ESS}(k) \leq 0 \quad PV_{ESS}(k) \geq 0 \quad (17)$$

Constraints (9)–(11) and (17) can be compactly re-written by

$$\mu_{dis}u(k) \leq \gamma_{dis} \quad (18)$$

where

$$\mu_{dis} = \begin{bmatrix} 0 & 0 & 0 & -eye(6) & 1 & 1 \\ 1 & 1 & 0 & 0 & 0 & 1 \\ 1 & 0 & 1 & 1 & 0 & 0 \\ & & & eye(6) & & \\ -1 & -1 & 0 & 0 & 0 & -1 \end{bmatrix} \quad \gamma_{ch} = \begin{bmatrix} zeros(6,1) \\ 0 \\ P_{LD}(k) \\ P_{PV}(k) \\ P_m^{max}ones(6,1) \\ PV_{GR}^{max} - P_{LD}(k) \end{bmatrix} \quad (19)$$

2.2. General Formulations of Deep Learning Techniques

Deep learning models are crucial for improving the control system's intelligence and adaptability. These models capture intricate patterns and correlations by using the benefits

of the temporal dependencies included in the data, allowing for real-time, updated control decisions. The hybrid control system includes integrations with the subsequent deep learning architectures.

2.2.1. Long Short-Term Memory

LSTM networks are a form of RNN architecture that addresses the vanishing gradient problem and captures long-range dependencies in sequential input. LSTM networks have specialized memory cells and gating mechanisms that allow them to retain and update information selectively across several steps.

The LSTM computation for each time step (k) is defined as follows:

$$h(k+1) = \text{LSTM}(u(k+1), h(k), c(k)) \quad (20)$$

where $u(k)$ is the input, $h(k)$ is the hidden state, and $c(k)$ is the cell state. The cell state serves as a long-term memory component, storing information across time, while the hidden state catches and transports short-term dependencies.

The LSTM architecture has three main gates: the input gate ($u(k)$), the forget gate ($f(k)$), and the output gate ($y(k)$). These gates control the flow of information into, out of, and within the LSTM cell, allowing it to filter out irrelevant facts while retaining useful information. Furthermore, LSTM cells have an internal memory cell ($u(k)$) that allows them to store and update data with time.

LSTM networks excel at capturing long-range dependencies, making them appropriate for tasks involving sequential data and complex temporal dynamics. In a hybrid control system, LSTM models are critical for learning and anticipating the temporal behavior of the MG system. LSTM-based control strategies improve the adaptability and performance of the hybrid control system by efficiently capturing and utilizing temporal relationships, resulting in increased efficiency and stability during MG operation.

2.2.2. Gated Recurrent Unit

GRU networks are a type of RNN architecture that looks like LSTM but has a simpler topology. GRUs are intended to capture long-term dependencies in sequential data while remaining computationally more efficient than LSTM networks.

At each time step (k), the GRU computation is described as follows:

$$h(k+1) = \text{GRU}(u(k+1), h(k)) \quad (21)$$

Unlike LSTM cells, GRU cells lack discrete memory cells and instead use a single concealed state to record both short-term and long-term reliance.

The GRU architecture consists of two primary gates: the reset gate ($r(k)$) and the update gate ($z(k)$). These gates, which regulate information flow within the GRU cell, allow the hidden state to be selectively updated based on the input and previous hidden states. The update gate determines how much of the new data should be absorbed, whereas the reset gate specifies how much of the old disguised state should be forgotten.

GRU networks achieve a balance between model complexity and performance, thereby being appropriate for tasks involving sequential data of intermediate complexity. In the context of a hybrid control system, GRU-based models provide an efficient and effective way to capture temporal dependencies and make sound control decisions. By exploiting GRU network capabilities, the hybrid control system improves adaptability and performance, increasing efficiency and stability in MG operation.

2.3. Integration of Rule-Based Control with Deep Learning Techniques

All experiments are run on an NVIDIA A100 and two Intel Xeon(R) CPUs @ 2.30GHz and 12 GB of memory. Although the data have been collected with care, some manipulations are needed. We first discussed the process used for dataset cleaning, and we grouped the

datasets to better represent the data in the RNN-based models we designed. We then carried out a search space of deep learning networks, which we evaluated as part of this work.

2.3.1. Dataset Preprocessing

Within this phase, we consider how to prepare the data for RNN-based deep networks since the data contain the hourly power recirculation of adaptive MG systems in a year. The dataset includes 13 attributes. To better represent the data in the RNN-based models that we have designed, we grouped them.

Accumulated: The column P_{LD} is the total need of the smart building; hence, the sum of the columns PV_{LD} , GR_{LD} , and BAT_{LD} fulfills it. The photovoltaic energy source P_{PV} distributes the power to the columns PV_{GR} , PV_{LD} , and PV_{BAT} .

Additional elements: The power needs in these columns are at negligible levels since WT , FC , EL , and FT require a small amount of power for ignition.

Main elements: Since the presented smart building system mainly circulates power within the LD , PV , GR , and BAT , the corresponding columns are considered the main elements.

As a result of the aforementioned details and correlation analysis (Figure 3), PV_{GR} , PV_{LD} , GR_{LD} , PV_{BAT} , and BAT_{LD} are left to be used in RNN models. Moreover, the first RNN-based models were trained using the different data portions to see the real-time effects of eliminated columns. Because these experiments resulted in negative R^2 values, it is considered that the column elimination process is cross-checked.

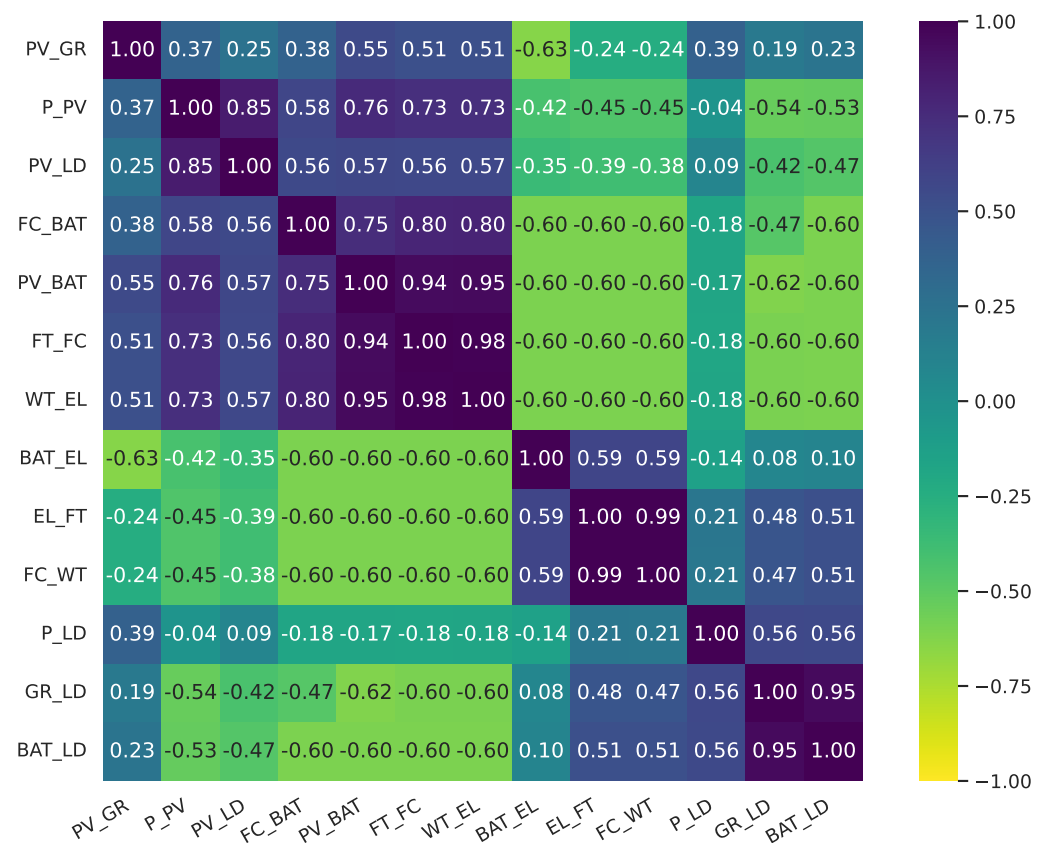


Figure 3. The correlation matrix of the power flows.

Several notable correlations are observed within the dataset in Figure 3. The power consumed from the grid (GR_{LD}) exhibits a significant positive correlation with power consumption (P_{LD}), indicating that grid power is a substantial contributor to the overall power consumption in the building.

Interestingly, there are negative correlations between certain attributes, such as between battery power consumption (BAT_{LD}) and power consumption from fuel cells (FC_{BAT}). This suggests that when one power source is utilized more, the other may be utilized less, indicating a potential trade-off or balancing act in power usage within the building.

Figure 4 depicts a comprehensive picture of power dynamics within the smart building, highlighting various properties across different time intervals. Several major observations arise from extensive research and are backed by particular numerical results:

- Significant changes in power qualities are found during different time periods. For example, on 31 May 2017, total power usage was 316.75 kWh, with PV generation accounting for 83.65 kWh, power from PV to the grid (PV_{GR}) 44.65 kWh, and electricity from PV to local distribution (PV_{LD}) 49.90 kWh. In contrast, on 31 March 2018, overall power consumption increased to 635.77 kWh, accompanied by changes in PV generation (192.31 kWh) and other power distribution components.
- Seasonal variations are evident in the dataset, with distinct trends observed across different months. For example, during the summer months, such as June and July 2017, both power consumption and generation peaked, indicating higher energy demand and increased solar irradiance. Conversely, in winter months, such as December 2017, power consumption remained relatively stable, while PV generation decreased due to reduced daylight hours.

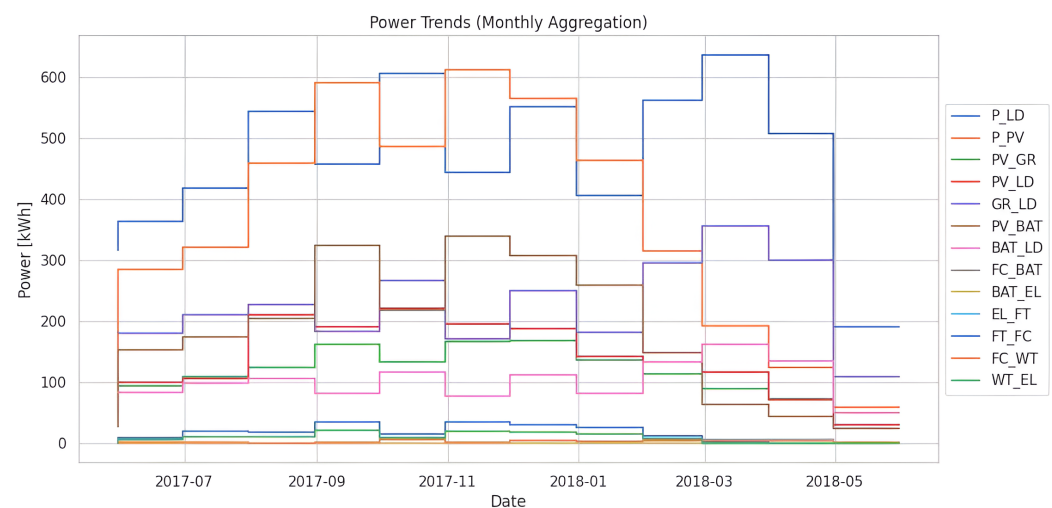


Figure 4. All monthly power trend data.

- Figure 4 underscores the role of RESs in power generation. For instance, on 30 April 2018, the PV contributed significantly to overall power generation, with PV generation reaching 124.53 kWh and WT to EL (WT_{EL}) at 0.33 kWh. These assets are crucial in reducing dependency on conventional grid power and mitigating environmental impact.
- ESSs, particularly batteries, facilitate efficient power management within the smart building. Notably, while certain power components such as FC_{BAT} , BAT_{EL} , EL_{FT} , FT_{FC} , FC_{WT} , and WT_{EL} are essential for energy transfer and system operation, their individual contributions to overall power consumption and generation are minimal. For instance, on 31 May 2017, FC_{BAT} , BAT_{EL} , EL_{FT} , FT_{FC} , FC_{WT} , and WT_{EL} collectively accounted for less than 1 kWh of power transfer.

In conclusion, the numerical results from the dataset provide valuable insights into the dynamics of power circulation within the smart building, emphasizing the importance of renewable energy integration, energy storage technologies, and efficient energy management practices. Further analysis and modelling based on these data can inform the development of sustainable and resilient smart building systems tailored to specific energy needs and environmental considerations.

2.3.2. Model and Hyperparameter Search

Deep learning networks' shape (layers and neurons per layer) significantly impacts performance [57]. We performed a search space for the most suitable solution for the obtained data. In order to prevent confusion from now on, we used the term RNN-based for all recurrent types of architectures. Since the possibility pool for experimental sets to be created with combinations of different parameters is infinite, we focused mainly on the effects of the types and number of RNN units, including the number of hidden states, optimizers, and learning rate schedulers.

RNN-based architectures: We identified three different variants of RNN-based approaches: simple RNN (sRNN), LSTM, and GRUs. The number of hidden states is restricted between 1 and 3. Initially, we started the experiments using the number of units in the hidden layers selected as multiples of the number of columns of the input data.

Optimizers: The optimizer decides how the neural network weights are adjusted following each training iteration. This study concentrates on three widely employed optimizers:

SGD (Stochastic Gradient Descent): SGD is the primary optimizer employed in deep learning. Although gradient descent theoretically updates the weights after processing each training sample, it is common to optimize the weights after processing each batch of data.

RMSprop (Root Mean Squared Propagation): RMSprop improves the performance of stochastic gradient descent (SGD) by including fading average partial gradients to adapt the step size of each parameter. This optimizer prioritizes recent gradients more.

Adam (ADaptive Moment estimation) [58]: Adam, like RMSprop, allocates specific learning rates to each parameter. While RMSprop calculates the average of the first moment, Adam also considers the average of the second moment when adjusting the learning rates.

Learning Rate Schedulers: Learning rate schedules aim to modify the learning rate when training by reducing the rate per a predetermined schedule. In this study, we used 4 common approaches:

Constant: As the name implies, the model does not change the learning rate during the training phase in this scheduler. We accept the default value as 0.001.

Time-Based Decay: This approach intends to reduce the learning over epochs, as seen in Equation (22). While lr and k are hyperparameters, the current learning and decay rates, t is the iteration number. As in the constant learning rate scheduler, we assign 0.001 as the initial learning rate. The decay rate is found by dividing the current learning rate by the current number of the epoch.

$$lr = \frac{lr_0}{(1 + kt)} \quad (22)$$

Step Decay: This learning rate schedule, where the number of epochs is a hyperparameter, reduces the learning rate by a factor every few epochs.

Exponential Decay: This schedule applies an exponential decay function to an optimizer step, based on a defined initial learning rate, as described in Equation (23).

$$lr = \frac{lr_0}{e^{(-kt)}} \quad (23)$$

2.3.3. Implementation Details

We used a 20–80 training–test split. Further, the training data were split into training and validation sets of 80% and 20%, respectively. When we refer to 'batch size' in the context of data analysis, it indicates the number of consecutive data points grouped together for processing. For instance, if we select a batch size of 7 for daily power consumption data, we organize the yearly dataset into segments of 7 consecutive days each. Each segment represents a week's worth of data. This approach facilitates the computational learning process by enabling the models to discern patterns and trends occurring every week. Therefore, opting for a batch size of 7 assists in examining and understanding the weekly variations in power consumption.

We employed the Glorot uniform initializer [59] to initialize the parameters within our networks. This initializer ensures that the weights are uniform across all layers regarding the variance of the activations, thereby preventing the gradient from either exploding or vanishing due to a consistent variance. After eliminating unnecessary columns, we obtained 5 columns, as mentioned earlier, and hence the output dense layer has 6 neurons.

After the first attempts, we discovered that the high number of epochs did not perform satisfactorily; thus, we kept it constant at 20. In addition, the constant learning rate performed better among other candidates, such as time-based decay, step decay, and exponential decay.

Finally, the activation function provides the non-linear element within the networks. Due to the nature of the case, the power consumption predictions in the output-dense layer should not produce negative values. To overcome this issue, we used ReLU. On the other hand, the activation functions of RNN-based layers were not interfered with.

Finally, the hidden state was defined to update the control decision of the proposed method. It is $h(k)$ at time step k and depicts the adaptive MG system's dynamics as learned by the RNN model. It encodes information about the MG system's current state using past observations and inputs.

The hidden state, $h(k)$, can be defined as follows [25]:

$$h(k) = [\text{SOC}^{\text{ESS}}(k)] \quad (24)$$

The hidden state captures the current SOC of the ESS, providing information about the energy storage level and potentially other relevant variables affecting the MG system dynamics.

In LSTM networks, the cell state $c(k)$ at time step k functions as a long-term memory component and complements the hidden state. It allows the model to capture long-range dependencies in the sequential data by storing and updating data over numerous time steps.

The cell state $c(k)$ in this situation can be described as follows:

$$c(k) = [f_{\text{GR}_{LD}}(k), f_{\text{ESS}_{GR}}(k)] \quad (25)$$

The forward-passed features $f_{\text{GR}_{LD}}$ and $f_{\text{ESS}_{GR}}$ represent the power flows from the GR to the LD and ESS to the GR. These features collect essential information about the MG system's power consumption and storage dynamics, which helps the model to predict future states and make control decisions.

In summary, the rule-based control logic serves as a basic control method, providing a framework for decision-making in the MG system. It can handle known scenarios and take prompt action based on specified rules. Deep learning models are used to supplement rule-based control by learning from data and delivering adaptive control actions in instances when rules may be insufficient or when the system confronts unexpected conditions. Deep learning models can detect complicated patterns and non-linear correlations in data and optimize control decisions. Then, a decision-making mechanism is created that dynamically switches between rule-based control and deep learning models based on the MG system's current state, performance metrics, or other relevant variables. For instance, the system may use rule-based control under typical settings but switch to deep learning models when there is much ambiguity or when dealing with new scenarios. Next, the integrated control strategy will be tested through simulation or real-world testing to confirm that it meets the MG system's objectives and criteria. Following that, its performance will be evaluated in terms of stability, efficiency, dependability, and flexibility in various working environments. To improve the iterative process, regularly monitor and analyze the performance of the integrated control strategy while gathering feedback from the adaptive MG system. Use this feedback to improve overall system performance by refining rule-based control logic, fine-tuning deep learning models, or adjusting the decision-making mechanism. By integrating rule-based control and deep learning methods, we can use both approaches to provide a more resilient, adaptive, and economical control strategy for the adaptive MG system.

3. Results and Discussions

3.1. The Results of the Rule-Based Control

This section examines the performance of the rule-based control system in managing energy consumption and storage within the smart building. The basic rule-based control system relies on predetermined rules and thresholds, with no machine learning or predictive modeling capabilities. We assess its performance by analyzing weekly load demand data, ESS configurations, and SOC metrics.

The weekly load demand represents the total power consumption within the smart building for that week, whereas the ESS configurations represent changes in energy storage capacity caused by charging or discharging activities. The SOC represents the proportion of energy stored compared to the ESS's full capacity.

Figure 5a illustrates how analyzing weekly load demand and ESS configurations reveals patterns in energy use and storage behavior. During weeks with higher load needs, the ESS configurations are adjusted to meet the increasing energy requirements. Conversely, periods with reduced load demands may see ESS charging activities performed to optimize energy utilization and sustain SOC levels. Figure 5b shows that ESS configurations discharge more to meet energy demands in weeks with high load demand, such as the 1st, 11th, and 42nd weeks. In contrast, during weeks with reduced load needs, such as the 35th and 48th weeks, the ESS setups demonstrate decreased discharge or even charging activities performed to maintain SOC values.

Figure 5c illustrates how the basic rule-based control system effectively manages energy storage and optimizes SOC levels. By keeping SOC within optimal ranges, the system maintains sufficient energy reserves to satisfy future load demands while preventing overcharging or discharging of the ESS. Analysis of SOC measurements shows that the rule-based control system effectively keeps SOC within acceptable limits, assuring the ESS's operational efficiency and durability. Throughout the monitoring period, SOC levels remained within the prescribed range, showing that energy storage resources were successfully managed.

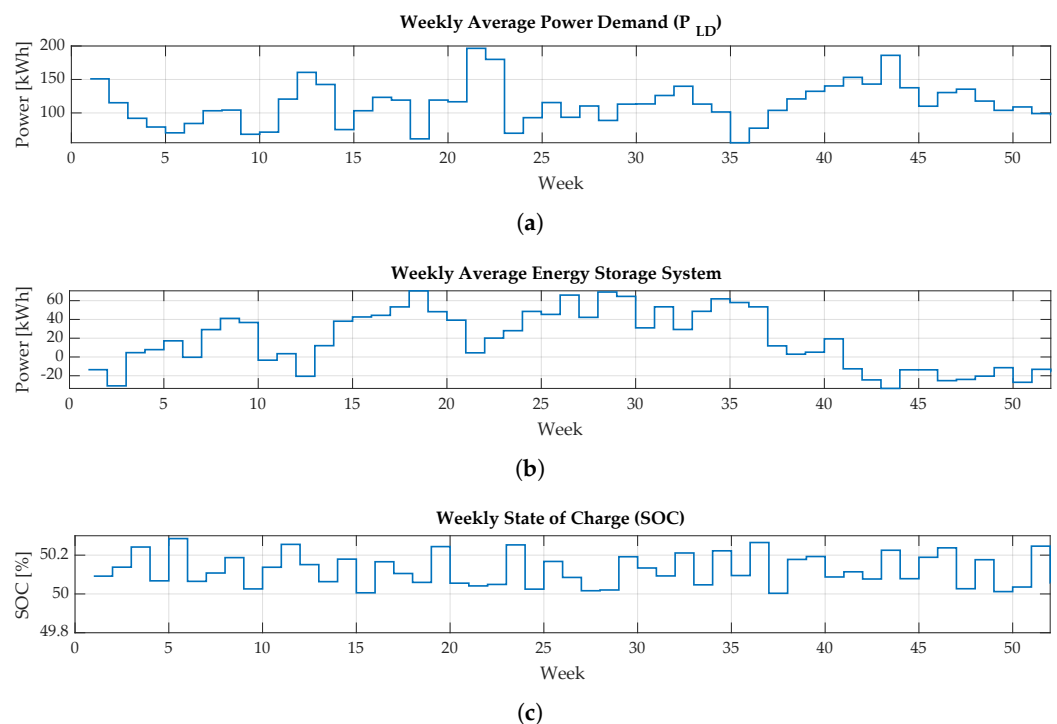


Figure 5. Results of power flows for (a) the load demand, (b) the ESS, and (c) the SOC of the ESS during the rule-based control.

The findings illustrate the effectiveness of the rule-based control system in regulating energy storage and consumption in the context of smart buildings. The system adapts to ranging load requirements by utilizing predetermined regulations and thresholds and optimizes energy consumption while preserving SOC levels within preferred intervals. However, it is essential to acknowledge the limitations of rule-based control systems, particularly in handling complex and dynamic environments. While effective for basic energy management tasks, rule-based systems may struggle to adapt to unforeseen circumstances or optimize energy usage based on historical data alone.

Next, the integration of machine learning techniques, such as predictive modeling and reinforcement learning, has been implemented to enhance the adaptability and intelligence of EMSs. By combining the strengths of rule-based control with the learning capabilities of machine learning algorithms, a hybrid approach known as hybrid intelligent control could offer superior performance and flexibility in managing smart building energy systems.

3.2. The Results of the Deep Learning Methods

We present the results of our model training. The main evaluation metrics are selected as R^2 , mean squared error (MSE), and mean absolute error (MAE). The evaluation metrics were obtained from test scores. Table 2 presents the top 20 performing models.

Table 2. The results of the best RNN-based architectures—order of R^2 .

Optimizer	LR_Sch	Batch Size	Arch_Details	Test_R2	Test_MSE	Test_MAE
adam	constant	7	GRU(50)	0.999809	0.000002	0.000831
adam	constant	7	GRU(15)	0.999780	0.000003	0.001037
adam	constant	7	LSTM(50)	0.999731	0.000003	0.000798
adam	constant	7	sRNN(50)	0.999468	0.000006	0.001499
rmsprop	constant	7	GRU(50)	0.999466	0.000055	0.001366
rmsprop	constant	7	sRNN(50)	0.999457	0.000005	0.001246
rmsprop	constant	7	GRU(15)	0.999223	0.000012	0.001820
adam	constant	7	LSTM(15)	0.999041	0.000010	0.001433
rmsprop	constant	7	GRU(15) + GRU(15)	0.998331	0.000022	0.002302
rmsprop	constant	7	LSTM(10)	0.997685	0.000026	0.002008
rmsprop	constant	7	GRU(50) + GRU(50) + GRU(50)	0.997464	0.000034	0.003154
rmsprop	constant	7	LSTM(50) + LSTM(50) + LSTM(50)	0.993648	0.000071	0.002782
adam	constant	7	LSTM(15) + LSTM(15) + LSTM(15)	0.989356	0.000117	0.002773
rmsprop	constant	7	LSTM(15) + LSTM(15) + LSTM(15)	0.983175	0.000175	0.004793
adam	constant	7	LSTM(10) + LSTM(10)	0.982457	0.000190	0.002483
rmsprop	constant	7	LSTM(5) + LSTM(5)	0.975035	0.000278	0.005464
sgd	constant	7	LSTM(10)	0.833051	0.001675	0.019741
sgd	constant	7	LSTM(5)	0.824882	0.001812	0.017543
adam	constant	7	sRNN(5)	0.797054	0.002377	0.017024
rmsprop	constant	7	GRU(5)	0.780668	0.002561	0.007525

Here, we present the architectural notation. Our neural network architecture consists of multiple recurrent layers, each with a customizable number of hidden states. Each integer value in brackets after the corresponding recurrent layers presents the number of units of the hidden state. Corresponding to this, e.g., $LSTM(50) + LSTM(50)$, means that the model has two hidden states with 50 units each.

Considering the top 20 cases in Table 2, none of the recurrent layers overwhelms the others. The best case was obtained from the single GRU with 50 units, with $\sim 0.99 R^2$ and almost 0 MSE and MAE.

We now summarize other design choices:

Optimizer: The experiments showed that no optimizers can be considered better than the others. Although the number of occurrences of SGD seems lower than the others, it is still a suitable candidate.

Learning Rate Scheduler: The constant learning rate schedule dominates the results.

Deepness of the Architecture: Considering the data set used, it has been observed that relatively shallow models give better results, regardless of the recurrent layer type.

Threats to Validity

In this section, we outline the constraints of the experimental part of our study and emphasize potential validity concerns stemming from these limitations. Our methodology is shaped by comparable endeavors in the systems performance literature (such as Eismann et al. [60]) and follows the approach adopted by Wohlin et al. [61].

L1 Infinite search space: Several factors limit the RNN-based model training process.

L2 Obtained results: This study is not a benchmarking of various models.

L3 Single power consumption dataset: This study uses only data from a single smart building.

L4 Single expert for model training: Although the search space has been discussed collaboratively, a single expert conducted the experimental designs of RNN-based models.

Now, let us examine the consequences of these constraints in relation to the concepts of search space, outputs, internal, and external validity.

Search Space: Although other parameter combinations may yield more promising models (Limitation L1), this study mainly focused on improving promising model designs.

Outputs: In the process of finding the most suitable RNN-based model for the data, the models that gave the best results (Limitation L2) in terms of evaluation metrics were taken into account.

Internal Validity: Our work involved cleaning the data to be amenable to analysis and machine learning. A single expert researcher observed the effects of eliminated columns in RNN-based models (Limitation L4), leaving the opportunity to misinterpret the columns. The processes undertaken were well documented to mitigate this impact, and two further researchers audited the process. The code of the whole process is made available to the community (<https://github.com/cengizmehmet/DeepRuleMG>, accessed on 6 April 2024).

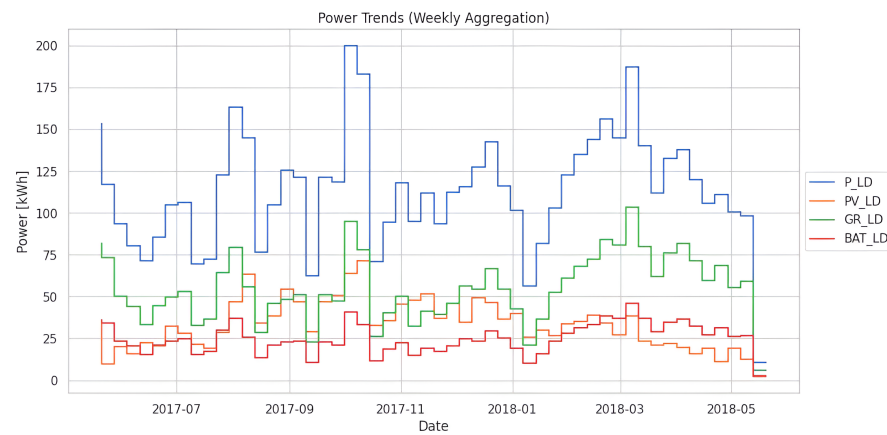
External Validity: This work predicts power consumption results from a single dataset (Limitation L3). Further work could have also evaluated whether to extend the existing data or add more data from various smart buildings.

3.3. The Results of the Hybrid Intelligent Control

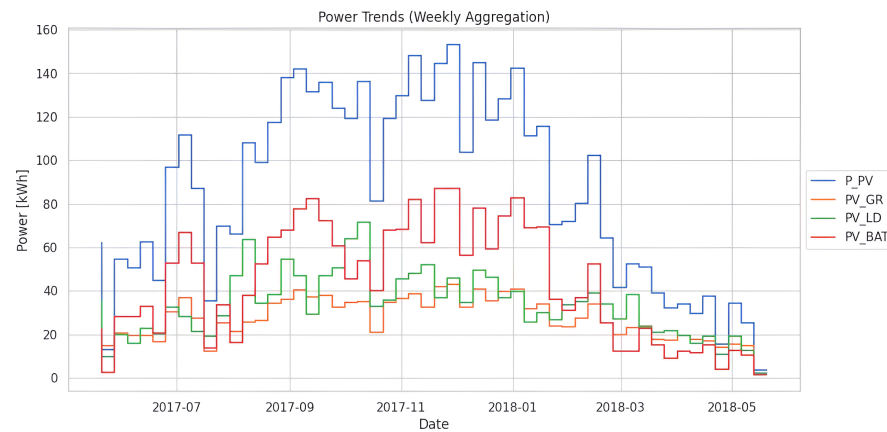
The weekly data for power attributes, including P_{PV} , GR_{LD} , PV_{LD} , and BAT_{LD} , provide valuable insights into the energy dynamics of the smart building. Our proposed method significantly improves energy management and efficiency by leveraging a combination of rule-based control and deep learning techniques.

- The weekly variations in power attributes reveal distinct patterns over time. The system optimizes energy utilization while minimizing wastage by integrating rule-based control strategies, such as scheduling power generation and consumption based on predicted demand. For example, on 4 June 2017, PV_{LD} and GR_{LD} exhibited lower

values than in previous weeks, indicating potential energy savings through load shifting or demand response mechanisms (see Figure 6a).



(a)



(b)

Figure 6. Power flows among the components of the adaptive MG system for (a) the load and (b) the PV.

- Deep learning techniques enhance the system's predictive capabilities, enabling accurate forecasting of power generation and consumption patterns. Through RNNs or LSTM models, the system can adapt to dynamic changes in energy demand and supply, optimizing decision-making processes in real-time. For instance, as shown in Figure 6b, on 13 August 2017, the system accurately predicted an increase in power consumption, allowing for proactive adjustments to grid interactions and energy storage. Deep learning models use features like PV_{BAT} and P_{PV} to estimate power generation and consumption trends, resulting in more accurate decision-making. On 4 June 2017, the incorporation of P_{PV} data allowed the system to predict increasing PV generation and proactively modify energy distribution and storage.
- Integrating battery systems, directed by rule-based control and informed by deep learning predictions, is critical for optimizing energy storage and distribution. Figure 6 shows that the system can intelligently manage battery charging and discharging cycles by considering PV_{BAT} and BAT_{LD} data in conjunction with other variables, such as PV_{LD} and GR_{LD} . The system decreases grid dependency and peak load demand by strategically charging and discharging batteries in response to predicted demand and generation. On 30 July 2017, BAT_{LD} data showed effective use of battery capacity to balance changes in PV_{LD} and GR_{LD} .

- The combination of basic rule-based control and deep learning provides synergistic benefits for energy management. Rule-based algorithms give deterministic guidance for system operation, but deep learning models improve adaptability and responsiveness to changing environmental conditions. By combining the benefits of both techniques, the system reaches peak energy efficiency, cost savings, and environmental sustainability performance.
- Our proposed solution is scalable and adaptable to various energy conditions and building environments. The system is adaptable to changing energy demands, renewable energy sources, and grid interactions, whether deployed in a residential, commercial, or industrial scenario. Furthermore, constant learning and refining of deep learning models ensures robustness and resistance to changing energy issues.

To summarize, combining the basic rule-based control and deep learning techniques into EMSs is a potential strategy for optimizing power utilization in smart buildings. The weekly power data analysis demonstrates the efficacy of our proposed strategy for increasing energy efficiency, lowering operational costs, and achieving sustainability goals. Further research and implementation initiatives can use these insights to encourage innovation in adaptive MG systems, resulting in a greener and more resilient energy future.

3.4. Comparative Analysis with Previous Research

Our study, focusing on rule-based control, deep learning, and hybrid intelligent control systems, contributes to the existing literature by comprehensively analysing their effectiveness in managing smart building energy systems. Previous studies [32,34,35] have examined similar approaches, and we present a comparative analysis here to contextualize our findings.

- **Rule-based Control Systems:** Our study aligns with previous research indicating that rule-based control systems effectively manage energy consumption and storage within smart buildings [11,49]. However, while traditional rule-based systems are suitable for basic energy management tasks, they may struggle to adapt to unforeseen circumstances or optimize energy usage based on historical data alone [40]. Our findings confirm these observations.
- **Deep Learning Methods:** In terms of deep learning methods, our study echoes the findings of [49], which suggested that integrating deep learning techniques enhances predictive capabilities, enabling accurate forecasting of power generation and consumption patterns. Our proposed hybrid intelligent control system confirms these observations, showing superior performance compared to standalone rule-based or deep learning methods.
- **Hybrid Intelligent Control Systems:** Our study introduces a hybrid intelligent control system, combining the strengths of rule-based control with the learning capabilities of machine learning algorithms. While [49] touched upon the potential of hybrid systems, our study provides concrete evidence of their effectiveness, showing significant improvements in energy management and efficiency compared to traditional rule-based or deep learning methods.

By providing a comparative analysis with previous research, our study not only confirms the existing body of knowledge but also contributes to a better understanding of the performance and limitations of rule-based control, deep learning, and hybrid intelligent control systems in managing smart building energy systems.

4. Conclusions

In conclusion, we found crucial variables in the dataset that substantially impact power dynamics in adaptive MG systems through correlation analysis and numerical validation. RNN models include attributes such as PV_{GR} , PV_{LD} , GR_{LD} , PV_{BAT} , and BAT_{LD} because of their correlation and predictive power. The correlation matrix (Figure 3) indicates significant connections between several power circulation variables, offering vital

insights for designing predictive models and optimizing power management strategies in smart buildings. One notable association is the positive relationship between grid power consumption (GR_{LD}) and overall power consumption (P_{LD}). Negative correlations between variables, such as battery power consumption (BAT_{LD}) and power consumption from fuel cells (FC_{BAT}), indicate potential trade-offs or balancing acts in power usage inside the building.

In the context of model development, our experiments with RNN-based architectures and hyperparameter optimization have yielded promising results. The top-performing models, as summarized in Table 2, exhibit high R^2 values and low MSE and MAE, indicating their efficacy in predicting power consumption and generation within the adaptive MG systems.

Key insights from our analysis include the following:

- The choice of optimizer and learning rate scheduler has a significant impact on model performance, with the constant learning rate scheduler consistently outperforming other schedules.
- Shallow RNN architectures with relatively few hidden states yield better results than deeper architectures.
- No single recurrent layer type (e.g., simple RNN, LSTM, GRU) emerges as superior, suggesting that the choice of architecture should be tailored to the specific characteristics of the dataset and modeling task.

Our proposed method, hybrid intelligent control for adaptive MG optimization, integrates rule-based control strategies with deep learning techniques to optimize power management within adaptive MG systems. This innovative approach leverages the strengths of both rule-based systems and machine learning algorithms to achieve adaptive and efficient energy management.

In future developments, enhancing visualization techniques [62] could significantly augment the effectiveness of energy management systems within smart buildings. Integrating predictive analytics and machine learning algorithms into visualization platforms can enable the forecasting of future energy demand and generation patterns. By leveraging historical data and predictive models, stakeholders can anticipate fluctuations in energy usage, optimize resource allocation, and proactively address energy management challenges.

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Abbreviations

The following abbreviations are used in this manuscript:

<i>BAT</i>	Battery
<i>CS</i>	Cuckoo Search
<i>EL</i>	Electrolyzer
<i>EMS</i>	Energy Management System
<i>ESS</i>	Energy Storage System
<i>FC</i>	Fuel Cell
<i>FT</i>	Fuel Tank
<i>GR</i>	Grid
<i>GRU</i>	Gated Recurrent Unit
<i>GOA</i>	Grasshopper Optimization Algorithm
<i>HRES</i>	Hybrid Renewable Energy System
<i>LD</i>	Load
<i>LSTM</i>	Long Short-Term Memory
<i>MAE</i>	Mean Absolute Error
<i>MG</i>	Microgrid
<i>MSE</i>	Mean Squared Error
<i>MPC</i>	Model Predictive Control
<i>MS</i>	Master–Slave
<i>PD</i>	Primal–dual
<i>PSO</i>	Particle Swarm Optimization
<i>PV</i>	Photovoltaic
<i>RESs</i>	Renewable Energy Sources
<i>RNN</i>	Recurrent Neural Network
<i>S-MPC</i>	Switched Model Predictive Control
<i>sRNN</i>	Simple Recurrent Neural Network
<i>TLBO</i>	Teaching Learning-based Optimization
<i>WT</i>	Water Tank
BAT_{LD}	Power flow from the <i>BAT</i> to the <i>LD</i>
BAT_{LD}^{max}	The maximum power flow from the <i>BAT</i> to the <i>LD</i>
BAT_{EL}	Power flow from the <i>BAT</i> to the <i>EL</i>
<i>C</i>	Battery capacity
$c(k)$	Internal memory cell at <i>k</i>
EL_{FT}	Power flow from the <i>EL</i> to the <i>FT</i>
$f(k)$	Forget gate at <i>k</i> time step
FC_{BAT}	Power flow from the <i>FC</i> to the <i>BAT</i>
FC_{WT}	Power flow from the <i>FC</i> to the <i>WT</i>
FT_{FC}	Power flow from the <i>FT</i> to the <i>FC</i>
GR_{LD}	Power flow from the <i>GR</i> to the <i>LD</i>
GR_{LD}^{max}	The maximum power flow from the <i>GR</i> to the <i>LD</i>
$h(k)$	Hidden state at <i>k</i> time step
$J(k)$	Cost function
N_c	Control horizon
P_{ESS}	The nominal capacity of the <i>ESS</i>
P_{LD}	Load demand
P_{PV}	Power generated from the <i>PV</i>
P_N	The power obtained from the upstream network
$P_{N^{max}}$	The network operator’s set boundary
PV_{BAT}	Power flow from the <i>PV</i> to the <i>BAT</i>
PV_{BAT}^{max}	The maximum power flow from the <i>PV</i> to the <i>BAT</i>
PV_{GR}	Power flow from the <i>PV</i> to the <i>GR</i>
PV_{GR}^{max}	The maximum power flow from the <i>PV</i> to the <i>GR</i>
PV_{LD}	Power flow from the <i>PV</i> to the <i>LD</i>
PV_{LD}^{max}	The maximum power flow from the <i>PV</i> to the <i>LD</i>
<i>SOC</i>	State of charge
SOC^{ESS}	The state of charge of the <i>ESS</i>
$SOC^{ESS_{min}}$	The minimum state of charge of the <i>ESS</i>

$SOC^{ESS_{max}}$	The maximum state of charge of the ESS
WT_{EL}	Power flow from the WT to the EL
$x(k)$	State vector at k time step
$y(k)$	Output vector at k time step
$u(k)$	Input vector at k time step
η_{ch}	Charging efficiency of the ESS
η_{dis}	Discharging efficiency of the ESS

References

1. Shezan, S.A.; Kamwa, I.; Ishraque, M.F.; Muyeen, S.M.; Hasan, K.N.; Saidur, R.; Rizvi, S.M.; Shafiullah, M.; Al-Sulaiman, F.A. Evaluation of different optimization techniques and control strategies of hybrid microgrid: A review. *Energies* **2023**, *16*, 1792. [\[CrossRef\]](#)
2. Beg, O.A.; Khan, A.A.; Rehman, W.U.; Hassan, A. A Review of AI-Based Cyber-Attack Detection and Mitigation in Microgrids. *Energies* **2023**, *16*, 7644. [\[CrossRef\]](#)
3. Mannini, R.; Darure, T.; Eynard, J.; Grieu, S. Predictive Energy Management of a Building-Integrated Microgrid: A Case Study. *Energies* **2024**, *17*, 1355. [\[CrossRef\]](#)
4. Giaouris, D.; Papadopoulos, A.I.; Voutetakis, S.; Papadopoulou, S.; Seferlis, P. A power grand composite curves approach for analysis and adaptive operation of renewable energy smart grids. *Clean Technol. Environ. Policy* **2015**, *17*, 1171–1193. [\[CrossRef\]](#)
5. Košťál, K.; Khilenko, V.; Hunák, M. Hierarchical Blockchain Energy Trading Platform and Microgrid Management Optimization. *Energies* **2024**, *17*, 1333. [\[CrossRef\]](#)
6. Giaouris, D.; Papadopoulos, A.I.; Seferlis, P.; Papadopoulou, S.; Voutetakis, S.; Stergiopoulos, F.; Elmasides, C. Optimum energy management in smart grids based on power pinch analysis. *Chem. Eng.* **2014**, *39*, 55–60.
7. Khawaja, Y.; Giaouris, D.; Patsios, H.; Dahidah, M. Optimal cost-based model for sizing grid-connected PV and battery energy system. In Proceedings of the 2017 IEEE Jordan Conference on Applied Electrical Engineering and Computing Technologies (AECT), Aqaba, Jordan, 11–13 October 2017; pp. 1–6.
8. Bashishtha, T.K.; Singh, V.P.; Yadav, U.K.; Varshney, T. Reaction Curve-Assisted Rule-Based PID Control Design for Islanded Microgrid. *Energies* **2024**, *17*, 1110. [\[CrossRef\]](#)
9. Versaci, M.; La Foresta, F. Fuzzy Approach for Managing Renewable Energy Flows for DC-Microgrid with Composite PV-WT Generators and Energy Storage System. *Energies* **2024**, *17*, 402. [\[CrossRef\]](#)
10. Gadoue, S.M.; Giaouris, D.; Finch, J.W. Tuning of PI speed controller in DTC of induction motor based on genetic algorithms and fuzzy logic schemes. In Proceedings of the 5th International Conference on Technology and Automation, Budapest, Hungary, 19–20 October 2005; pp. 85–90.
11. Allahham, A.; Greenwood, D.; Patsios, C.; Taylor, P. Adaptive receding horizon control for battery energy storage management with age-and-operation-dependent efficiency and degradation. *Electr. Power Syst. Res.* **2022**, *209*, 107936. [\[CrossRef\]](#)
12. Pervez, M.; Kamal, T.; Fernández-Ramírez, L.M. A novel switched model predictive control of wind turbines using artificial neural network-Markov chains prediction with load mitigation. *Ain Shams Eng. J.* **2022**, *13*, 101577. [\[CrossRef\]](#)
13. Khawaja, Y.; Qiqieh, I.; Alzubi, J.; Alzubi, O.; Allahham, A.; Giaouris, D. Design of cost-based sizing and energy management framework for standalone microgrid using reinforcement learning. *Sol. Energy* **2023**, *251*, 249–260. [\[CrossRef\]](#)
14. Zhu, J.; Chen, J.; Zhuo, Y.; Mo, X.; Guo, Y.; Liu, L.; Liu, M. Stochastic energy management of active distribution network based on improved approximate dynamic programming. *IEEE Trans. Smart Grid* **2021**, *13*, 406–416. [\[CrossRef\]](#)
15. Aaslid, P.; Korpås, M.; Belsnes, M.M.; Fosso, O.B. Stochastic optimization of microgrid operation with renewable generation and energy storages. *IEEE Trans. Sustain. Energy* **2022**, *13*, 1481–1491. [\[CrossRef\]](#)
16. Wang, X.; Hua, Q.; Liu, P.; Sun, L. Stochastic dynamic programming based optimal energy scheduling for a hybrid fuel cell/PV/battery system under uncertainty. *Process. Saf. Environ. Prot.* **2022**, *165*, 380–386. [\[CrossRef\]](#)
17. Pamulapati, T.; Cavus, M.; Odigwe, I.; Allahham, A.; Walker, S.; Giaouris, D. A review of microgrid energy management strategies from the energy trilemma perspective. *Energies* **2022**, *16*, 289. [\[CrossRef\]](#)
18. Spiliopoulos, N.; Sarantakos, I.; Nikkhah, S.; Gkizas, G.; Giaouris, D.; Taylor, P.; Rajarathnam, U.; Wade, N. Peer-to-peer energy trading for improving economic and resilient operation of microgrids. *Renew. Energy* **2022**, *199*, 517–535. [\[CrossRef\]](#)
19. Suresh, M.C.V.; Edward, J.B. A hybrid algorithm based optimal placement of DG units for loss reduction in the distribution system. *Appl. Soft Comput.* **2020**, *91*, 106191. [\[CrossRef\]](#)
20. Wang, Y.; Liu, S.; Sun, B.; Li, X. A distributed proximal primal–dual algorithm for energy management with transmission losses in smart grid. *IEEE Trans. Ind. Informatics* **2022**, *18*, 7608–7618. [\[CrossRef\]](#)
21. Liu, L.-N.; Yang, G.-H. Distributed optimal energy management for integrated energy systems. *IEEE Trans. Ind. Informatics* **2022**, *18*, 6569–6580. [\[CrossRef\]](#)
22. Cavus, M.; Allahham, A.; Adhikari, K.; Zangiabadia, M.; Giaouris, D. Control of microgrids using an enhanced Model Predictive Controller. In Proceedings of the 11th International Conference on Power Electronics, Machines and Drives (PEMD 2022), Newcastle, UK, 21–23 June 2022.

23. Cavus, M.; Allahham, A.; Adhikari, K.; Zangiabadi, M.; Giaouris, D. Energy Management of Microgrids Using a Flexible Hybrid Predictive Controller. In Proceedings of the 2nd World Energy Conference and 7th UK Energy Storage Conference, Birmingham, UK, 12–14 October 2022.
24. Cavus, M.; Allahham, A.; Adhikari, K.; Zangiabadi, M.; Giaouris, D. Energy management of grid-connected microgrids using an optimal systems approach. *IEEE Access* **2023**, *11*, 9907–9919. [\[CrossRef\]](#)
25. Cavus, M.; Allahham, A.; Adhikari, K.; Giaouris, D. A hybrid method based on logic predictive controller for flexible hybrid microgrid with plug-and-play capabilities. *Appl. Energy* **2024**, *359*, 122752. [\[CrossRef\]](#)
26. Cavus, M.; Ugurluoglu, Y.F.; Ayan, H.; Allahham, A.; Adhikari, K.; Giaouris, D. Switched Auto-Regressive Neural Control (S-ANC) for Energy Management of Hybrid Microgrids. *Appl. Sci.* **2023**, *13*, 11744. [\[CrossRef\]](#)
27. Rahmani, E.; Mohammadi, S.; Zadehbagheri, M.; Kiani, M. Probabilistic reliability management of energy storage systems in connected/islanding microgrids with renewable energy. *Electr. Power Syst. Res.* **2023**, *214*, 108891. [\[CrossRef\]](#)
28. Zhang, X.; Guan, J.; Zhang, B. A master slave peer to peer integration microgrid control strategy based on communication. In Proceedings of the 2016 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC), Xi'an, China, 25–28 October 2016; pp. 1106–1110.
29. Pang, K.; Wang, C.; Hatziargyriou, N.D.; Wen, F.; Xue, Y. Formulation of radiality constraints for optimal microgrid formation. *IEEE Trans. Power Syst.* **2022**, *38*, 5341–5355. [\[CrossRef\]](#)
30. Mansouri Kouhestani, F.; Byrne, J.; Johnson, D.; Spencer, L.; Brown, B.; Hazendonk, P.; Scott, J. Multi-criteria PSO-based optimal design of grid-connected hybrid renewable energy systems. *Int. J. Green Energy* **2020**, *17*, 617–631. [\[CrossRef\]](#)
31. Sharifzadeh, M.; Sikinioti-Lock, A.; Shah, N. Machine-learning methods for integrated renewable power generation: A comparative study of artificial neural networks, support vector regression, and Gaussian Process Regression. *Renew. Sustain. Energy Rev.* **2019**, *108*, 513–538. [\[CrossRef\]](#)
32. Benti, N.E.; Chaka, M.D.; Semie, A.G. Forecasting renewable energy generation with machine learning and deep learning: Current advances and future prospects. *Sustainability* **2023**, *15*, 7087. [\[CrossRef\]](#)
33. Moradzadeh, A.; Zakeri, S.; Shoaran, M.; Mohammadi-Ivatloo, B.; Mohammadi, F. Short-term load forecasting of microgrid via hybrid support vector regression and long short-term memory algorithms. *Sustainability* **2020**, *12*, 7076. [\[CrossRef\]](#)
34. Kim, H.J.; Kim, M.K. A novel deep learning-based forecasting model optimized by heuristic algorithm for energy management of microgrid. *Appl. Energy* **2023**, *332*, 120525. [\[CrossRef\]](#)
35. Khan, M.R.; Haider, Z.M.; Malik, F.H.; Almasoudi, F.M.; Alatawi, K.S.S.; Bhutta, M.S. A Comprehensive Review of Microgrid Energy Management Strategies Considering Electric Vehicles, Energy Storage Systems, and AI Techniques. *Processes* **2024**, *12*, 270. [\[CrossRef\]](#)
36. Rastegarparnah, A.; Asif, M.E.; Stolkin, R. Hybrid Neural Networks for Enhanced Predictions of Remaining Useful Life in Lithium-Ion Batteries. *Batteries* **2024**, *10*, 106. [\[CrossRef\]](#)
37. Han, H.; Neira-Molina, H.; Khan, A.; Fang, M.; Mahmoud, H.A.; Awwad, E.M.; Ahmed, B.; Ghadi, Y.Y. Advanced series decomposition with a gated recurrent unit and graph convolutional neural network for non-stationary data patterns. *J. Cloud Comput.* **2024**, *13*, 20. [\[CrossRef\]](#)
38. Gupta, B.B.; Chui, K.T.; Gaurav, A.; Arya, V.; Chaurasia, P. A Novel Hybrid Convolutional Neural Network-and Gated Recurrent Unit-Based Paradigm for IoT Network Traffic Attack Detection in Smart Cities. *Sensors* **2023**, *23*, 8686. [\[CrossRef\]](#) [\[PubMed\]](#)
39. Oviedo, R.J.M.; Fan, Z.; Gormus, S.; Kulkarni, P.; Kaleshi, D. Residential energy demand management in smart grids. In Proceedings of the PES T&D 2012, Orlando, FL, USA, 7–10 May 2012; pp. 1–8.
40. Libao, F.J.D.; Dizon, R.O. Rule-based energy management strategy for hybrid electric road train. In 2018 IEEE 10th International Conference on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment and Management (HNICEM), Baguio City, Philippines, 29 November–2 December 2018; pp. 1–4.
41. Sanaye, S.; Sarrafi, A. A novel energy management method based on Deep Q Network algorithm for low operating cost of an integrated hybrid system. *Energy Rep.* **2021**, *7*, 2647–2663. [\[CrossRef\]](#)
42. Abdul Basit, N.A.I.; Rosmin, N.; Mustaamal, A.H.; Hussin, S.M.; Said, D.M. A Simple Energy Management System for a Micro Grid System Using Rule-Based Algorithm. In *Control, Instrumentation and Mechatronics: Theory and Practice*; Springer: Berlin/Heidelberg, Germany, 2022; pp. 273–284.
43. Sansa, I.; Boussaada, Z.; Bellaaj, N.M. Solar Radiation Prediction Using a Novel Hybrid Model of ARMA and NARX. *Energies* **2021**, *14*, 6920. [\[CrossRef\]](#)
44. Brahma, B.; Wadhvani, R. Solar irradiance forecasting based on deep learning methodologies and multi-site data. *Symmetry* **2020**, *12*, 1830. [\[CrossRef\]](#)
45. Samanta, I.S.; Panda, S.; Rout, P.K.; Bajaj, M.; Piecha, M.; Blazek, V.; Prokop, L. A comprehensive review of deep-learning applications to power quality analysis. *Energies* **2023**, *16*, 4406. [\[CrossRef\]](#)
46. Schmidt, R.M. Recurrent neural networks (rnns): A gentle introduction and overview. *arXiv* **2019**, arXiv:1912.05911.
47. Amidi, A.; Amidi, S. *Vip Cheatsheet: Recurrent Neural Networks*; Stanford University: Stanford, CA, USA, 2018.
48. Xia, Y.; Yu, F.; Xiong, X.; Huang, Q.; Zhou, Q. A Novel Microgrid Islanding Detection Algorithm Based on a Multi-Feature Improved LSTM. *Energies* **2022**, *15*, 2810. [\[CrossRef\]](#)
49. Lee, D.; Arigi, A.M.; Kim, J. Algorithm for autonomous power-increase operation using deep reinforcement learning and a rule-based system. *IEEE Access* **2020**, *8*, 196727–196746. [\[CrossRef\]](#)

50. Xu, C.; Huang, Y. Integrated Demand Response in Multi-Energy Microgrids: A Deep Reinforcement Learning-Based Approach. *Energies* **2023**, *16*, 4769. [[CrossRef](#)]
51. Succetti, F.; Rosato, A.; Araneo, R.; Di Lorenzo, G.; Panella, M. Challenges and Perspectives of Smart Grid Systems in Islands: A Real Case Study. *Energies* **2023**, *16*, 583. [[CrossRef](#)]
52. Sorouri, H.; Oshnoei, A.; Novak, M.; Blaabjerg, F.; Anvari-Moghaddam, A. Learning-Based Model Predictive Control of DC-DC Buck Converters in DC Microgrids: A Multi-Agent Deep Reinforcement Learning Approach. *Energies* **2022**, *15*, 5399. [[CrossRef](#)]
53. Chang, C.; Zhao, W.; Wang, C.; Song, Y. A novel energy management strategy integrating deep reinforcement learning and rule based on condition identification. *IEEE Trans. Veh. Technol.* **2022**, *72*, 1674–1688. [[CrossRef](#)]
54. Allahham, A.; Greenwood, D.; Patsios, C. Incorporating Ageing Parameters into Optimal Energy Management of Distribution Connected Energy Storage. *AIM* **2019**, 1763–1767.
55. Allahham, A.; Greenwood, D.; Patsios, C.; Walker, S.L.; Taylor, P. Primary frequency response from hydrogen-based bidirectional vector coupling storage: modelling and demonstration using power-hardware-in-the-loop simulation. *Front. Energy Res.* **2023**, *11*, 1217070. [[CrossRef](#)]
56. Sökmen, K.F.; Çavuş, M. Review of batteries thermal problems and thermal management systems. *J. Innov. Sci. Eng. (JISE)* **2017**, *1*, 35–55.
57. Cengiz, M.; Forshaw, M.; Atapour-Abarghouei, A.; McGough, A.S. Predicting the performance of a computing system with deep networks. In Proceedings of the 2023 ACM/SPEC International Conference on Performance Engineering (ICPE '23), Association for Computing Machinery, New York, NY, USA, 15–19 April 2023; pp. 91–98.
58. Kingma, D.P.; Ba, J. Adam: A method for stochastic optimization. *arXiv* **2014**, arXiv:1412.6980.
59. Glorot, X.; Bengio, Y. Understanding the difficulty of training deep feedforward neural networks. In Proceedings of the Thirteenth International Conference on Artificial Intelligence and Statistics (AISTATS '10), Sardinia, Italy, 13–15 May 2010; pp. 249–256.
60. Eismann, S.; Costa, D.E.; Liao, L.; Bezemer, C.P.; Shang, W.; van Hoorn, A.; Kounev, S. A case study on the stability of performance tests for serverless applications. *J. Syst. Softw.* **2022**, *189*, 111294. [[CrossRef](#)]
61. Wohlin, C.; Runeson, P.; Höst, M.; Ohlsson, M.C.; Regnell, B.; Wesslén, A. *Experimentation in Software Engineering*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2012.
62. Akbulut, O.; McLaughlin, L.; Xin, T.; Forshaw, M.; Holliman, N.S. Visualizing ordered bivariate data on node-link diagrams. *Vis. Informatics* **2023**, *7*, 22–36. [[CrossRef](#)]

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