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An Economic Control Strategy for Energy Dispatch for Hybrids in a Microgrid

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ABSTRACT

The recent surge in electricity demand across industrial, commercial, transportation, and residential sectors has led to the emergence of hybrid energy systems, integrating renewable energy sources and energy storage systems to meet dynamic electricity requirements. This study introduces a control system as an operational strategy, defining an operational policy for an energy management system based on hybrid systems. The control system development considers the dynamic behavior of energy demand, energy purchase and sale prices in the market, and energy unit prices resulting from the implementation hybrid systems. The findings suggest that incorporating a control system in energy management is crucial for achieving enhanced economic performance in energy supply. Additionally, the impact of the hybrid system's operation, determining the timing and quantity of energy supply from both generated and stored sources, is evaluated. Simulation results demonstrate the effectiveness of the proposed control in providing benefits and comfort for both flexible and inflexible loads. The contributions of this research lie in the development of a comprehensive control system for hybrid energy systems, highlighting its significance in optimizing economic performance and operational efficiency. The findings underscore the practical benefits of the proposed control strategy in enhancing energy supply management and meeting diverse load requirements.

1. INTRODUCTION

Over the past few years, the demand for electricity has increased exponentially in the building, industrial, agricultural, and transportation sectors. As a result, the generation of electricity has also increased. Furthermore, the governmental sectors have been influenced by concerns regarding global warming and climate change in the formulation and implementation of public policies aimed at mitigating these concerns. Despite the dominance of fossil fuels, public policies have encouraged the use of renewable energy sources, such as solar and wind power. In 2011, 20% of global energy production was from renewable sources, with 2% coming from solar and wind. By 2021, solar and wind power generation will surpass 10% of the total global electric power generation for the first time [1]. The combination of solar generators and wind turbines provides a high level of reliability. Nonetheless, the adoption of renewable power generation systems has been impeded by issues pertaining to the stochastic power generation of renewable energy technologies [2].

A hybrid system, which includes a hybrid renewable energy source (HRES) connected to an energy storage system (ESS), a bidirectional converter, and a charge-discharge controller, is evaluated based on reliability, flexibility, affordability, efficiency, environmental protection, stability, durability, sustainability, optimization, and control of operation in a microgrid [2]-[3]. The increasing prevalence of this issue has prompted further consideration of the MG concept in the power sector, with the aim of reducing greenhouse gas emissions and minimizing energy prices [4]. The MG control structure encompasses three control objectives, namely primary control, secondary control, and tertiary control. The primary control system monitors the maximum output of renewable energy generators. The secondary control system bears the responsibility for ensuring power quality and maintaining synchronization with the utility grid. The tertiary control system is responsible for monitoring, controlling, and managing the power dispatch of renewable energy sources and energy storage systems, as well as minimizing energy costs, reducing greenhouse gas emissions, and maximizing the life cycle of energy storage systems [5]-[7].

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Therefore, it is essential to develop and implement energy control dispatch strategies in existing EMS, taking into account the behavior of energy demand, energy purchase and sale prices in the energy market, energy unit prices derived from the implementation of HRES and ESS, and even environmental conditions. In this particular context, contemplating a control system model for an energy management system (EMS) represents an alternative that may be implemented. This system model has enormous potential when determining the maximum energy that each HRES must provide to the MG given the demand required by the consuming system. These models can be used to integrate energy storage systems into HRES, thus allowing the decision to dispatch surplus energy to be made at what time. A control system model for an EMS considers factors such as the available parameters of renewable energy sources and the energy storage system, the load demand, and the price of energy. The input parameters are processed by the control of an EMS, and the outputs of the EMS display the optimal energy exchange between the HRES, the ESS, the MG, and the utility grid, as depicted in Figure 1. The control model for an EMS incorporates economic factors to establish the operational policy. From an economic point of view, energy costs are reduced by making the HRES and ESS more efficient and operating conditions better, which makes the life cycle of the energy as long as possible.

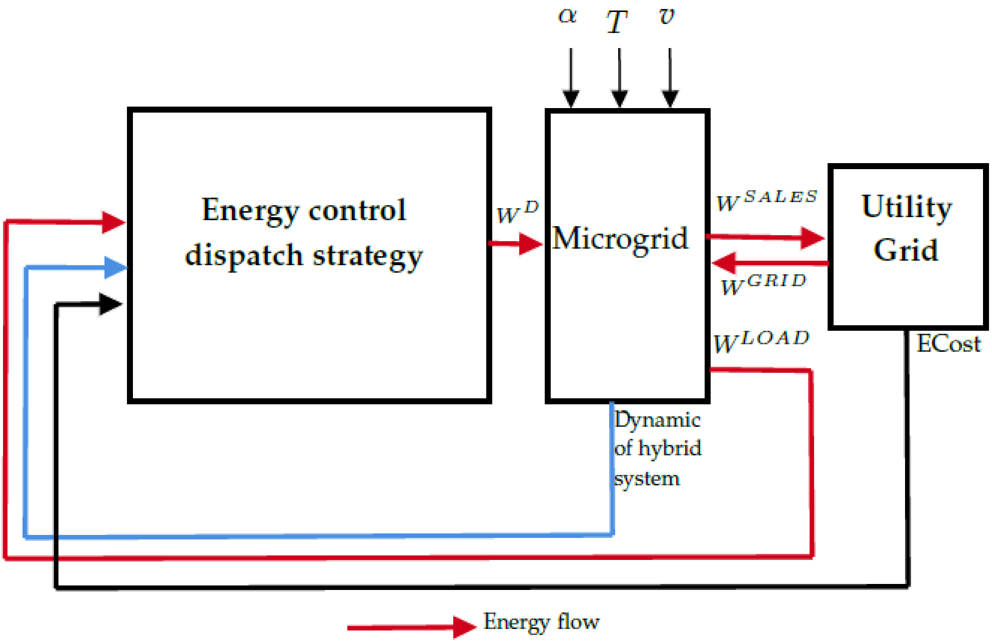


Fig. 1. A control system model for an energy management system framework for microgrid.

However, when considering energy dispatch from an energy management modeling standpoint, the recent literature has only developed models with optimization approaches that seek to reduce the energy cost in the grid. These models typically focus on energy dispatch strategies [8]-[9], whereas other authors refer to them as operational strategies [10]-[11]. For example, an optimal operating strategy can be found for the efficient supply of electricity in a microgrid consisting of academic buildings using a mixed-integer programming model, and the cost difference between the operating strategy and the scenario without it is reported as two main scenarios [12].

A second-order mixed-integer programming model is presented for an EMS that operates in isolated and connected mode. This model is utilized to minimize the amount of energy sent to the microgrid and the cost of energy sent by the HRES and ESS [13]. Instead, a particle swarm optimization model has been developed to evaluate the impact of self-discharge in energy storage systems on energy cost. Additionally, it is evaluated that integrated renewable energy sources require less energy storage, providing higher reliability and better economic performance [14]. Nonetheless, a common assumption in EMS modeling by optimization considers the daily cost of electricity, assuming either deterministic or stochastic energy prices and incorporating uncertain demand [15]. It is rare that an EMS control system model has been presented that defines the optimal operating policies for a hybrid renewable energy system, considering unit energy prices derived from HRES and ESS. However, few models have been presented that define the optimal operating policies for a hybrid renewable energy system, considering both unit energy prices derived from HRES and ESS [16]-[17]. Nonetheless, the majority of the works examined in the review pertain to EMS modeling within the framework of mathematical programming or heuristic models, assuming the quality of main grid power dispatch and the cost of market energy as a function of the optimal sizes of HRES and ESS. They fail to consider the unit energy prices derived from the implementation of the ESS, nor do they consider the greenhouse gas emissions in HRES and ESS for energy dispatch.

Further, an innovative approach for the optimal scheduling of distributed energy resources in a low voltage microgrid system with the objective of minimizing the total cost of generation is presented in [22]. The study highlights the importance of demand response in achieving efficient and sustainable operation and highlights the need for strategies that promote clean and economical energy management in microgrids.

In contrast, in [23], a demand response program that addresses the carbon-constrained economic dispatch problem in a microgrid system is proposed. The study emphasizes the importance of sustainable energy management and optimization of microgrid operation to reduce carbon emissions, offering an innovative solution to improve efficiency and environmental sustainability in microgrid systems.

When considering the implementation of energy management systems to meet end-user energy demand and reduce energy costs throughout the day, it is essential to take these factors into consideration. This research proposes a control system model for an EMS, in which a trade-off solution determines an operation policy that minimizes energy costs by increasing efficiency and operating conditions in HRES and ESS, as well as minimizing greenhouse gas emissions. The main contributions are listed in the paragraph below:

- A control system model for an energy management system integrated with hybrid renewable energy systems and an energy storage system is presented to mitigate energy use from the utility grid.
- A solution to the control model problem for the energy management system of a hybrid power system and an energy storage system is presented.
- It examines how the energy storage system interacts with the energy market and what impact this has on both the economic impact.

The rest of this paper is organized as follows: “Methodology”, where the problem is presented and the control system model for the energy management system is presented; “Results and Discussion”, and, finally, “Conclusions”.

2. METHODOLOGY

2.1 *Technology Framework*

In this work, a microgrid, as shown in Figure 2, includes photovoltaic panels and a wind turbine, a battery bank, a charge, and discharge battery controller, a utility grid, and a demand system. The energy generated by the HRES is incorporated into the demand system. The energy that exceeds the demand system requirements is stored in an energy storage system, and it is transmitted to the grid during periods of low-energy production by the hybrid renewable energy system. However, during high demand periods, power can be purchased from the grid if the HRES and ESS lack sufficient capacity to meet the demand. Nonetheless, during periods of excess power generation by the HRES, the energy can be transferred to the grid, resulting in a beneficial economic outcome.

The control system of an EMS allows for the management of variations in demand, ambient temperature, and wind speed throughout the day. Although the control system is a deterministic model, it allows for consideration of diverse scenarios and responds to distinct seasonal variations throughout the year, as well as incorporating energy price fluctuations at any given moment. It is also feasible to establish an operational policy that is based on variations in the demand and available resources of the HRES and the energy storage system. The control system model has two objectives: to minimize economic cost and greenhouse gas emissions, while the other is to ensure the supply of energy demanded by the load.

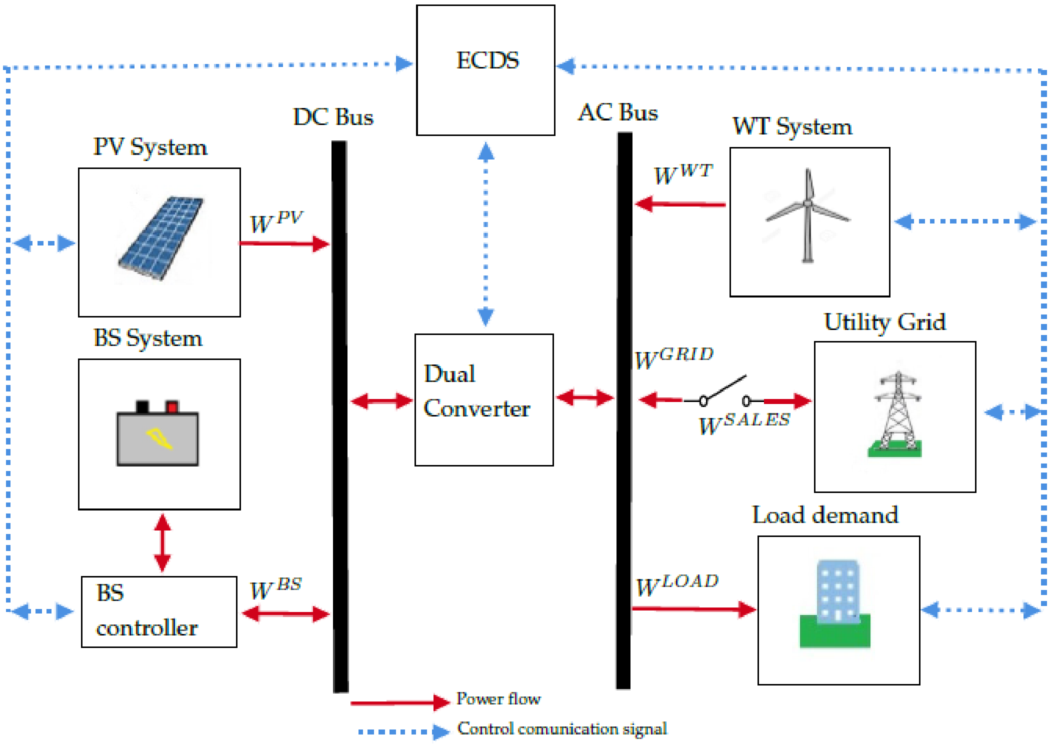


Fig. 2. Proposed scheme for the microgrid problem addressed.

2.2 Problem Definition

The system under consideration is described in Figure 3. The collection of available data, including solar irradiation, temperature, and wind speed, energy consumption profile, electric utility grid power price, capital costs, equipment maintenance, and operating costs, as well as greenhouse gas emissions, is imperative for the issue addressed in this paper. As shown in Figure 3, it is essential to meet multiple criteria involving economic considerations in order to guarantee at all times the energy demand required by the demand. The objective of this study is to identify a compromise solution that establishes the operational guidelines in the HRES and ESS based on the implementation of a control model for an EMS. The EMS must allocate energy from the HRES and ESS to the MG in order to guarantee an optimal dispatch on an economic basis.

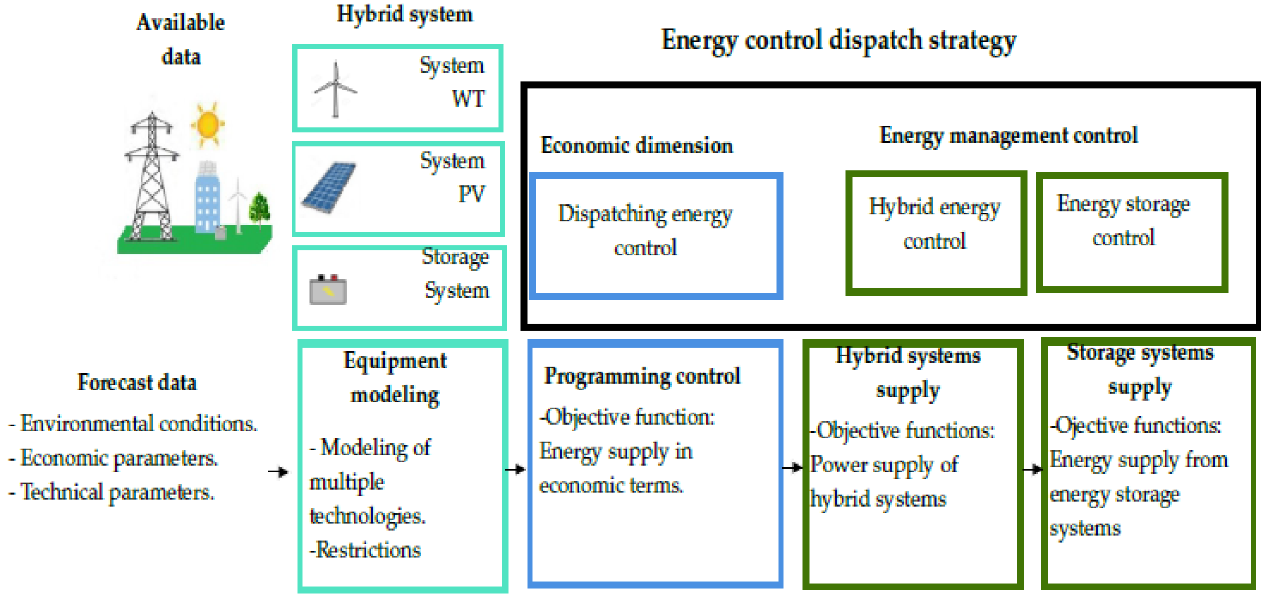


Fig. 3. Problem definition.

The control system of an EMS is integrated into two stages: scheduling planning and dispatch planning. The first stage determines the unit price of energy generated by the HRES and stored by the ESS based on the optimal size of the photovoltaic system, wind turbine, and battery bank implemented in the MG, as well as the unit emission of greenhouse gases for each of the devices connected to the MG. The second stage ensures the supply of energy needed to meet demand. It determines the amount of energy generated by each HRES unit and calculates the amount of energy to be supplied to the demand. In the event of energy surpluses, the load on the energy storage system is regulated at this stage. Alternately, in the event that the generation of energy by the HRES is insufficient to guarantee the required demand, the control system will release the energy stored in the ESS, ensuring that the requested energy is continuously supplied. The discharge is calculated considering the market price of energy, in the MG unit energy prices and unit emissions, all of them obtained in the first stage. Moreover, the cost of energy within the utility grid is taken into account. With the above measures in place, an economic dispatch of energy is assured, maximizing the consumption of energy generated by the HRES and minimizing the consumption of energy from the utility grid.

Furthermore, the operation policy of the control system in the EMS takes into consideration a multi-period approach and continuous evaluation. It also implies the following:

- The energy of each HRES and ESS is calculated.
- The time the EMS should dispatch power from the HRES and ESS to the MG should ensure that the economic objective is met.
- The required amount of energy each HRES, ESS, and utility grid must dispatch to supply the required demand is obtained.
- The control system requires energy market prices for electric energy.
- The state of charge of the energy storage system is estimated, taking into consideration the charging, discharging, and self-discharging efficiencies. Two additional restrictions, a maximum charge and a minimum charge, are also considered in order to prevent the battery from deep discharging, thus increasing its useful life.

Considering HRES and BS as state variables allows observing the state space at each instant and therefore establishing an operation policy according to the load requirements of the residential building. The economic evaluation includes system operation costs associated with the purchase of all system equipment, as well as system operation greenhouse emission from the system and unit energy costs for dispatch at each moment.

2.3 Microgrid Modeling Methodological Foundation Proposal

In the forthcoming section, the model of each device that integrates the microgrid based on hybrid renewable energy systems will be depicted. The proposed models allow for the determination of the behavior of the microgrid over time. Similarly, the proposed model inputs encompass solar irradiation, wind speed, temperature, and energy demand. At each moment of sampling, the power of each technology is calculated.

2.3.1 Power balance in the microgrid

The hourly demand for electricity required by a residential building can be met either by using a hybrid system or directly by using a utility grid, and this depends on the season of the year. Therefore, the power balance is achieved using energy from the photovoltaic system (W^{PV}), a wind turbine (W^{WT}), a battery bank (W^{BS}) and utility grid (W^{GRID}) and incomes from energy sales (W^{SALES}).

$$W^{D} - W^{LOAD} = 0$$

Where $W^{D} = W^{PV} + W^{WT} + W^{BS} + W^{GRID} + W^{SALES}$ (1)

2.3.2 Equipment modeling: photovoltaic, wind turbine and battery system.

PV system modeling

The output power of a PV systems depends of the area (A^{PV}) and the efficiency of solar collector (η^{PV}) as well as solar irradiance (α). The basic expressions for defining a PV system is presented in [18]:

$$W^{PV} = \alpha \cdot \eta^{PV} \cdot A^{PV} \tag{2}$$

The efficiency of solar collector is defined by the ambient temperature conditions.

$$\eta^{PV} = \eta_0^{PV}\left[1 - \beta_{ref}(T^{amb} - T^{ref})\right] \tag{3}$$

where η_0^{PV} is the design efficiency, β_{ref} the temperature coefficient associated with the material of the solar collector, T^{amb} is the ambient temperature and T^{ref} is the temperature associated with η_0^{PV}. A common value for T^{ref} is 25°C.

WT system modeling

Power generation for WT system (W^{WT}) is define by wind speed υ and swept area of units installed A^{WT}. Reported nonlinear expressions, based on the correlation wind speed–power production analysis, of different systems conformed by horizontal axis wind turbines [19].

$$W^{WT} = (a \cdot \upsilon + \mathrm{b} \cdot \upsilon^2) \cdot A^{WT} \tag{4}$$

BS system modeling

Batteries are used to store electricity when the supply for PV and WT is more than consumption. The energy stored in a battery system can be estimated by appropriate assessment of the state of charge (SOC) of the battery. The SOC after certain time (t) as given by the following equations [2].

Charging mode:

$$W^{BS}(t+1) = W^{BS}(t)(1 - \sigma^{BS}) + surplus \cdot \eta^{BS_c} \tag{5}$$

Discharging mode:

$$W^{BS}(t+1) = W^{BS}(t)(1 - \sigma^{BS}) - deficit/\eta^{BS_d} \tag{6}$$

where σ^{BS} is the battery self-discharging rate, $\eta^{BS_c}$is the charging efficiency and η^{BS_d} is the discharging efficiency. According [20]-[21], $\eta^{BS_c} = 90\%$, $\eta^{BS_d} = 85\%$ and $\sigma^{BS} = 0.2\%$ have been considered.

2.3.3 Constraint for technological framework

The models above are subject to various constraints that are not omitted from the control system model. The characteristics of these constraints are operation and design. The first design constraint we have is for the photovoltaic systems, which is that the installation area A^{PV} cannot be larger than the roof of the residential building A^{B} considered as our demand system.

$$A^{PV} \leq A^{B} \tag{7}$$

The following constraints are required for charging and discharging the battery bank integrated into the MG.

$$SOC_{min} \leq SOC \leq SOC_{max} \tag{8}$$

$$E^{\mu} \geq B^{BS} \tag{9}$$

$$SOC \leq BS_c \leq SOC_{max} \tag{10}$$

$$SOC_{min} \leq BS_d \leq SOC_{max} \tag{11}$$

where SOC_{min} and SOC_{max} represent the minimum and maximum parameters within which the battery can be charged and discharged, in order to prevent prolonged charges and discharges. The size in kWh of the battery depends on the size of the battery. On the contrary, BS_c and BS_d are states of charge and discharge, respectively. Finally, the energy stored B^{BS} is defined by the inlets from the PV and WT, on the other hand, the size of the battery system is represented by E^{μ}.

2.3.4 System operation costs

Economic dimension

The trade-off solution for an EMS requires an economic analysis in order to obtain, in terms of cost, the unit price of energy (price/kW) of each technology integrated into the MG. One method of evaluating costs is to analyze the cost of capital. The Total Annual Cost (TAC) is the sum of the annual costs and revenues of the microgrid. It consists of the total capital cost (CCost), operation and maintenance cost (OMCost), the cost of the energy from the utility grid (ECost), and income from energy sales (ESales). The capital costs of the units are determined by the fixed costs of the equipment. These economic values are usually accompanied by installation and base cost estimates. Furthermore, variable costs are dependent on the size of the system. The scale parameter adjusts the capital cost of the equipment as a function of the unit size. The annual factor is dependent on the interest rate and lifetime of the project. Below are described the cost functions of each subsystem.

$$TAC = CCost + OMCost + ECost - ESales \tag{12}$$

Capital cost

$$CCost = CCost^{BS} + CCost^{PV} + CCost^{WT} \tag{13}$$

$$CCost = \varphi(\xi^{BS} + \xi^{PV} + \xi^{WT} + size^{PV} \cdot A^{PV} + size^{WT} \cdot A^{WT} + size^{BS} \cdot E^{\mu}) \tag{14}$$

Operation and maintenance cost

$$OMCost = OMCost^{BS} + OMCost^{PV} + OMCost^{WT} \tag{15}$$

$$OCost = [\Psi^{GRID}(t) \cdot \mathrm{W}^{GRID}(t)] \tag{16}$$

$$ESales = [W^{PV} + W^{WT} + W^{BS} - W^{LOAD}] \tag{17}$$

3. CONTROL STRATEGY FOR SCHEDULING AND DISPATCH OF ENERGY FOR AN EMS

In an EMS, the optimal power dispatch strategy can be formulated using a control system model problem, as shown in Figure 4. This problem can be used to control excess power generation. The objective of this approach is to achieve economic objectives while balancing technical and economic constraints. The proposed control system design is designed to achieve optimal energy dispatch while also minimizing energy consumption costs.

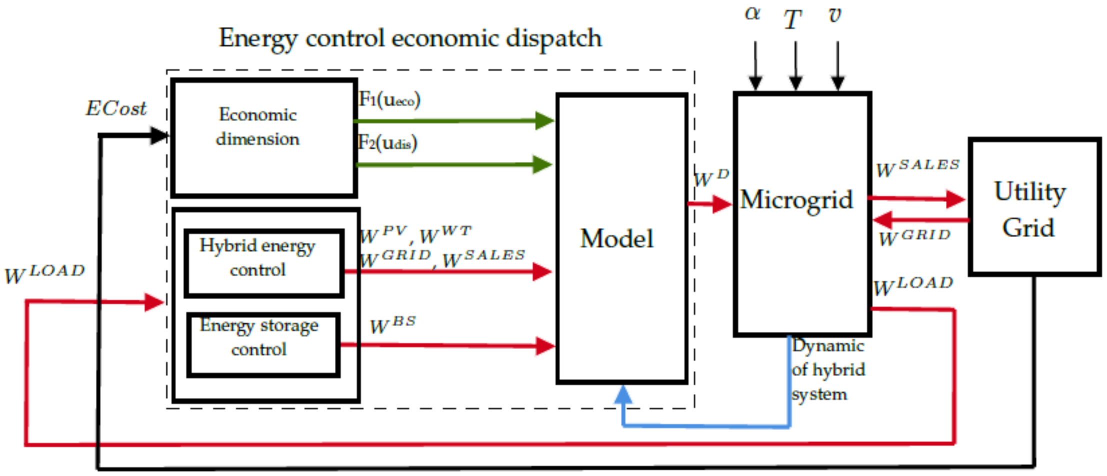


Fig. 4. An energy dispatch control framework for microgrids.

The derived values are transmitted to the hybrid energy management and storage levels for delivery to the managing MG and ultimately to the grid. The optimal operating level of the MG is determined by maximizing utilization from local production (W^{PV}, W^{WT}) and minimizing the cost of energy consumption. At the energy management control level, information on MG energy prices ($Ecost$), load demand (W^{LOAD}), HRES generation levels (W^{PV}, W^{WT}), and ESS energy storage levels (W^{BS}) is used to determine the values of energy exchanged with the main grid. An economically optimal energy dispatch (W^{D}) for and MG has therefore been determined.

From the models developed for each technology connected to the MG, it is possible to combine them into an equation (18), such as Equation 1, which corresponds to the compromise solution of the control system implemented in an EMS for operation in an MG.

$$\begin{gathered} W^{D} - W^{LOAD} = 0 \\ x^{T} F_2(u_{eco}) F_1(u_{dis}) - W^{LOAD} = 0 \end{gathered} \tag{18}$$

where the power demand is a function $W^{D} : \mathbb{R}^5 \rightarrow \mathbb{R}$ meeting residential building demand $W^{LOAD} \in \mathbb{R}$. Let $F_2(u_{eco})$ be a square matrix of order 5 discrete on $[0,1] \times [0,1]$ describing is defined as economic dispatch, $F_1(u_{dis})$ which corresponds to the energy that each technology can deliver to the MG at time t and how the dispatch matrices, respectively.

The solution to Equation (18) of this control system model is presented in Equation 19, which introduces a control that provides maximum energy dispatch while minimizing both energy consumption costs and minimizing the number of battery discharge cycles.

$$\begin{bmatrix} W^{PV} \\ W^{WT} \\ W^{BS} \\ W^{GRID} \\ W^{SALES} \end{bmatrix}^T = \begin{bmatrix} u_{1,1}^{eco} & 0 & 0 & 0 & 0 \\ 0 & u_{2,2}^{eco} & 0 & 0 & 0 \\ 0 & 0 & u_{3,3}^{eco} & 0 & 0 \\ 0 & 0 & 0 & u_{4,4}^{eco} & 0 \\ 0 & 0 & 0 & 0 & u_{5,5}^{eco} \end{bmatrix} \begin{bmatrix} u_1^{dis} \\ u_2^{dis} \\ u_3^{dis} \\ u_4^{dis} \\ u_5^{dis} \end{bmatrix} - W^{LOAD} = 0 \tag{19}$$

where;

$$F_2(u_{eco}) = \begin{bmatrix} u_{1,1}^{eco} & 0 & 0 & 0 & 0 \\ 0 & u_{2,2}^{eco} & 0 & 0 & 0 \\ 0 & 0 & u_{3,3}^{eco} & 0 & 0 \\ 0 & 0 & 0 & u_{4,4}^{eco} & 0 \\ 0 & 0 & 0 & 0 & u_{5,5}^{eco} \end{bmatrix}$$

$$; \begin{cases} u_{1,1}^{eco} = \begin{cases} 1 \; if \; W_{cost}^{PV} < Ecost \\ 0 \; if \; W_{cost}^{PV} \geq Ecost \end{cases} \\ u_{2,2}^{eco} = \begin{cases} 1 \; if \; W_{cost}^{WT} < Ecost \\ 0 \; if \; W_{cost}^{WT} \geq Ecost \end{cases} \\ u_{3,3}^{eco} = \begin{cases} 1 \; if \; BS_{cost} < Ecost \\ 0 \; if \; BS_{cost} \geq Ecost \end{cases} \\ u_{4,4}^{eco} = \begin{cases} 1 \; if \; W_{cost}^{GRID} < Ecost \\ 0 \; if \; W_{cost}^{GRID} \geq Ecost \end{cases} \\ u_{5,5}^{eco} = 1 \end{cases} \tag{20}$$

$$F_1(u_{dis}) = \begin{bmatrix} u_1^{dis} \\ u_2^{dis} \\ u_3^{dis} \\ u_4^{dis} \\ u_5^{dis} \end{bmatrix}$$

$$; \begin{cases} u_1^{dis} = 1 \\ u_2^{dis} = 1 \\ u_3^{dis} = 1 \\ u_4^{dis} = \begin{cases} 1 \; if \; W^{PV} + W^{WT} + W^{BS} < W^{LOAD} \\ 0 \; if \; W^{PV} + W^{WT} + W^{BS} \geq W^{LOAD} \end{cases} \\ u_5^{dis} = \begin{cases} 1 \; if \; (W^{PV} + W^{WT} > W^{LOAD}) \&\& (W^{BS} == SOC_{max}) \\ 0 \; if \; otherwise \end{cases} \end{cases} \tag{21}$$

If the price of the battery bank's energy is higher than that of the utility grid, the battery bank will be reliant solely on the utility grid's energy $u_{3,3}^{eco} = \{0\}$ If the power supply from the battery bank is less than the battery bank's capacity, the power supply will be provided by the battery bank's energy storage $u_{3,3}^{eco} = \{1\}$. On condition that the combined power generated from the PV and WT is sufficient to meet the load demand, the load will be served solely by these two sources $u_3^{dis} = u_4^{dis} = u_5^{dis} = \{0\}$. The excess power generated by PV and WT will be stored in a battery bank if the load demand exceeds the generated power. If the combined power from the PV and WT is insufficient to meet the load demand, the load will be served by the two sources and battery $u_3^{dis} = \{1\}, u_1^{dis} = u_2^{dis} = u_4^{dis} = u_5^{dis} = \{0\}$.

The equation (18) modeled the operation of an EMS in a general renewable microgrid with high-efficiency solar cells and a battery bank in a general renewable microgrid with high-efficiency solar cells. As the model is universal, it is applicable to any form of microgrid architecture (whether AC or DC), hybrid renewable energy sources, or storage technologies. Moreover, the developed model is capable of effortlessly capturing the inherent and authentic characteristics of the microgrid, its primary parameters, and the characteristics of the microgrid manufacturers. Furthermore, the proposed model incorporates both technical and economic parameters that are essential for the optimal management of the microgrid in both the short and long-term

4. CASE STUDY

A study was conducted to demonstrate the extent of the proposed control system, based on the electrical demand in a residential building located in the northern region of Mexico. The environmental conditions at the site are characterized by a dearth of wind energy, whereas solar radiation and temperature exhibit a consistent pattern throughout the year. In this study, four variables are examined: temperature, solar radiation, wind speed, and the demand for electrical energy in residential buildings. Figure 5 shows the average values of the four parameters considered for the four seasons of the year that feed the control system. The residential building requires a maximum load of 40 kWh. For the spring, summer, autumn, and winter load profiles, four different load profiles are considered for the spring, summer, summer, autumn, and winter.

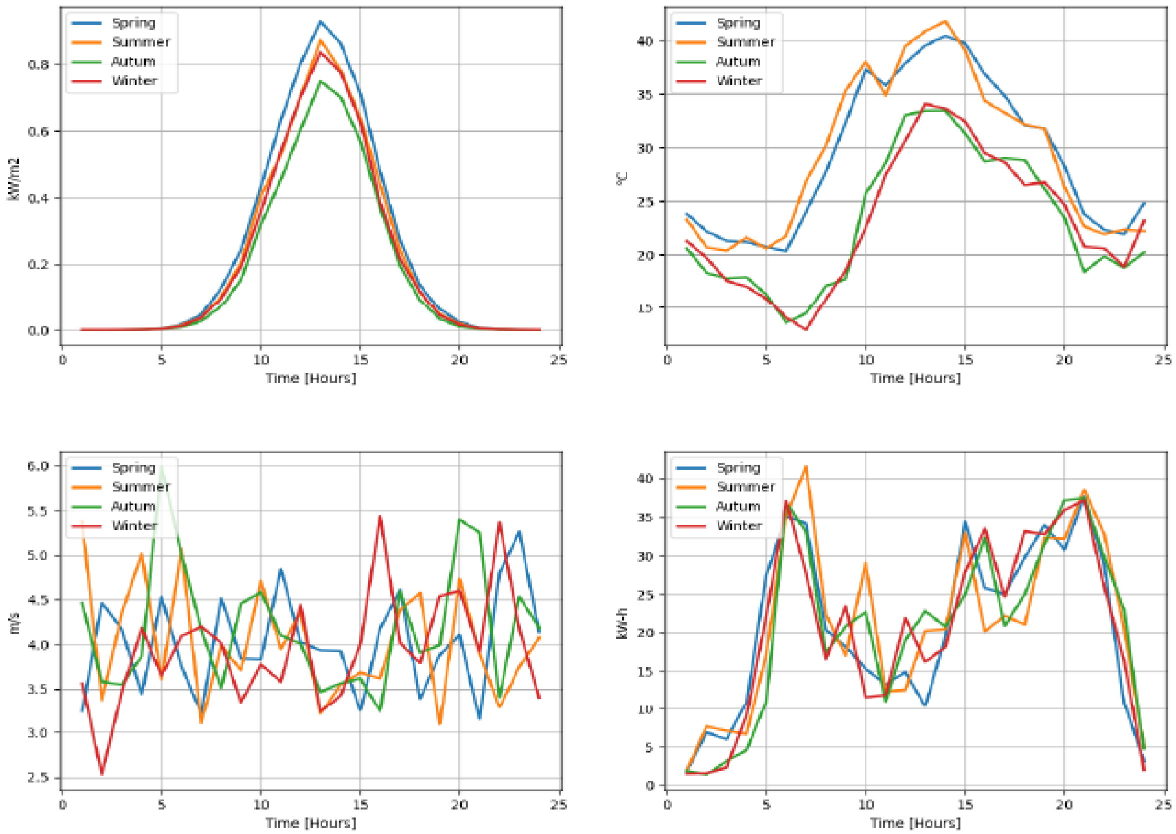


Fig. 5. Ambient parameters.

Table 1 provides an overview of the hybrid system's economic and technical characteristics. The sizing of photovoltaic panels, wind turbines, and battery systems was determined utilizing a nonlinear programming model with the aim of minimizing the total annual cost and constraints. The capacity of the wind turbine is 26 kW, whereas the capacity of the PV panels and batteries is 32 kW. The proposed microgrids total cost consists of the wind turbine, solar panel, battery bank, and converter.

Table 1. Electrical system sizing.

Parameter	Value
Annual operating cost	$ 21,733.83
PV size (kW)	37 kW
WT size (kW)	26 kW
BS size (kW)	32 kW

Singh *et al.* (2016) derived the economic parameters for PV, battery, and converter. The National Renewable Energy Center (CENER) of the Government of Mexico takes into account the economic parameters of all components, as depicted in Table 2.

5. RESULTS AND DISCUSSION

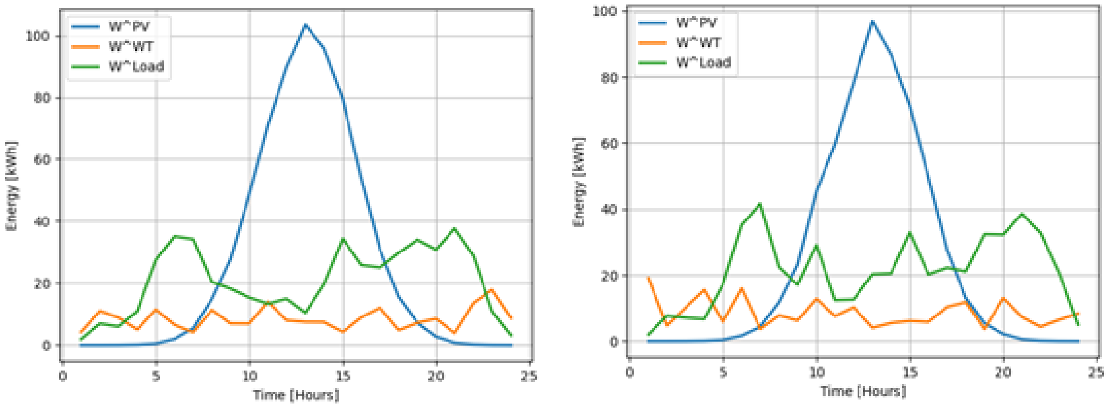
In order to demonstrate the adaptability of the EMS operation in response to energy demands, the results of the control system are intended to demonstrate the trade-off solution to the economic functions. This control focuses on the production of renewable energy and the maximization of energy dispatch under economic assumptions. This approach is employed to compare the values of the total annual cost and energy generation in order to determine the optimal control operation policy. It is important to note that this model utilizes specific parameters.

Table 2. Parameters values and costs

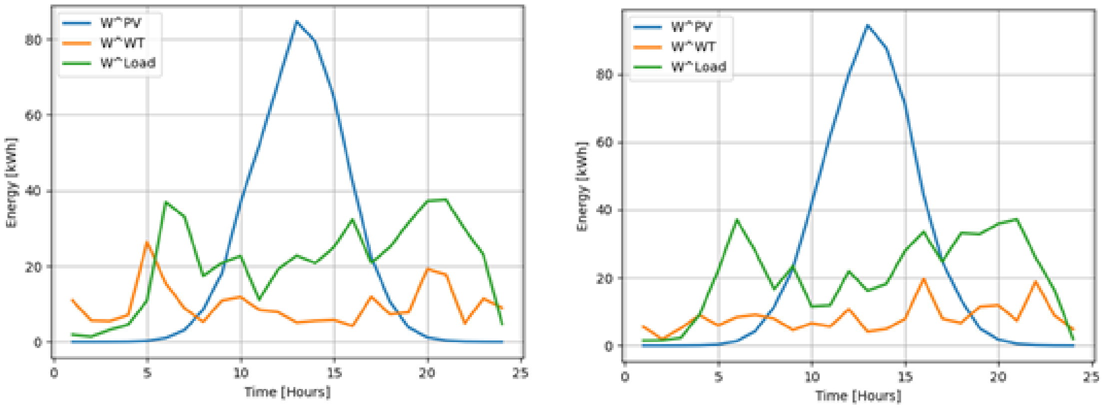
Parameter	Value
Fixed cost PV	$ 80
Fixed cost WT	$ 200
Fixed cost BS	$ 176
Variable cost PV	883 $/kW
Variable cost WT	1,350 $/kw
Variable cost BS	260 $/kW
Operating and maintenance cost per PV unit	$ 0.000003
Operating and maintenance cost per WT unit	$ 0.03
Operating and maintenance cost per BS unit	$ 0.000012
Unit cost of energy	0.05 $/kWh
Annualization factor	0.24 $/kWh

These changes may require additional modifications to the model. For example, changing the given conditions of temperatures, efficiencies of the photovoltaic system, wind turbine and battery, installation surfaces in the photovoltaic systems, and sweep in the wind turbine, costs, and operating conditions of some equipment, *etc*. It is important to note that if an analysis is performed for a different geographical area, the temperatures necessary for the correct operation of the system may not be met. Furthermore, the adjustment of the parameters may result in a change in the operation policy of the ESM.

The measurement of SOC, charge and discharge current, and round-trip efficiency of a battery bank are sensitive issues. The seasonal energy balance for the proposed microgrid is illustrated in Figure 6. The microgrid continues to possess excess electricity resulting from 51% of the total load, which is dispatched to the main power grid and the storage system. This excess electricity can subsequently be marketed. The evaluation of the hybrid system's performance is conducted over the course of a complete year of operation. The average of the full-time seasons has been selected from the entire year of operation for the purpose of this discussion.



(a) Spring (b) Summer



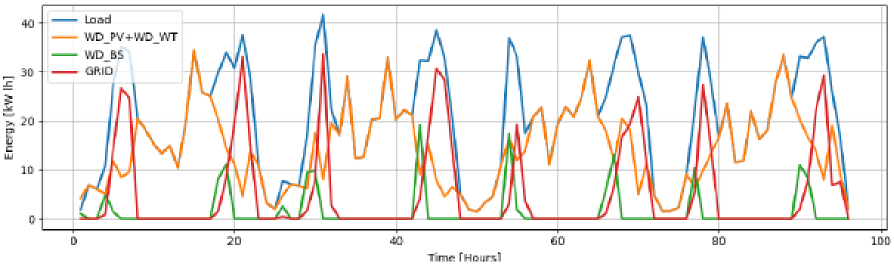
(c) Autum (d) Winter

Fig. 6. Full-year seasonal energy balance for the proposed microgrid.

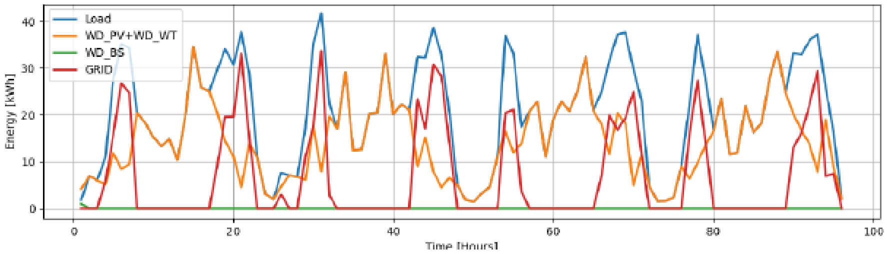
The control algorithm determines the maximum available electrical energy from every device in relation to its cost at a given moment. Furthermore, it is established that if there is a surplus of energy and an economic benefit, it can be sent off-grid.

The responses of the system are depicted in Figure 7, omitting the control algorithm and incorporating the economic objective. The system depicted in Figure 7a is unaffected by economic control, whereas the system depicted in Figure 7b is impacted by economic control. The x-axis in these plots denotes the durations of spring, summer, autumn, and winter, respectively. The y-axis denotes the electrical energy generated by every device that is connected to the grid. As the demand for electrical energy fluctuates, the control algorithm provides energy in accordance with the energy cost.

The proposed control system utilizes the optimal solution for network dimensioning shown in Table 3, as well as information on electrical energy costs for each device, as shown in Table 2. Moreover, it can be observed that in systems that lack control, it is imperative to charge and discharge the energy storage system, whereas in systems that have control derived from energy prices, an energy storage system is unnecessary as it is only charged once and not discharged. The seasonal variation in energy prices is reflected in the fundamental character of the energy supply. The control system will consistently provide the amount of energy required by the load, which will be supplied by each of the hybrid systems in accordance with the energy price at that particular moment. Based on the above, it is not necessary to implement an energy storage system, since it would result in an increase in the operation of the microgrid. In all situations, wind speed, and solar irradiation levels are not sufficient to meet energy demand using small-scale systems. The utilization of all available resources may not be sufficient to cater to the energy requirements of users. The reliance on renewable energy sources will necessitate an increase in electricity storage capacity due to environmental factors. The behavior of the battery system size reflects this. The associated costs of batteries and PV systems, as well as associated capital expenditures, significantly increase the economic burden. Nonetheless, in this particular case study, a storage system is not deemed necessary due to the control algorithm's economic objective function.

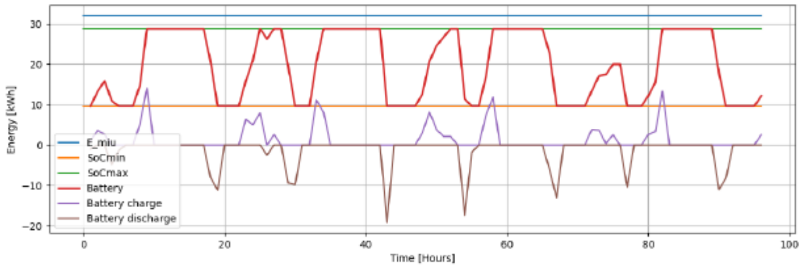


(a) An uncontrolled power supply.

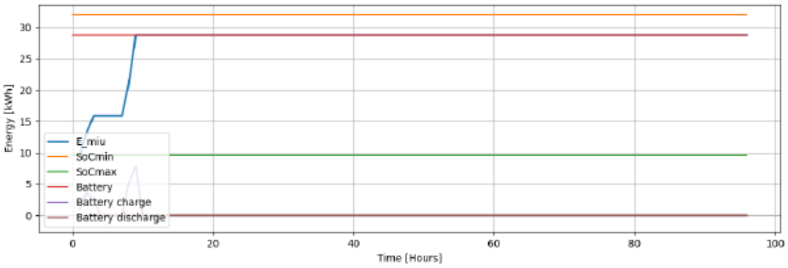


(b) A controlled power supply.

Fig. 7. Without and with control algorithm, energy dispatch.



(a) Battery power dispatch without control.



(b) Battery power dispatching with control.

Fig. 8. Battery model.

However, Figure 8a shows that, in the case of a storage system without a control algorithm, the SOC remains between 100% and 30% in all scenarios, in addition to having at least one loading and unloading response. The storage system is charged once in the first corresponding scenario in spring, and it is not discharged during the entire year of operation. Therefore, a storage system is not necessary for this. See Figure 8b.

From an economic standpoint, it is evident that certain topological reconfigurations are advantageous for the network, as the kWh cost of each hybrid system imposes limitations on the supply of energy to the load connected to the microgrid. However, in the absence of a control system with an economic objective function, a storage system is imperative. However, if you were to consider the economic objective function, you should not consider an energy storage system. This is the reason

Figure 8b shows that the battery response is that it only charges and no longer discharges.

Specifically, in the absence of an economic control algorithm, the battery is required to ensure the economic equilibrium, whereas the implementation of the economic control algorithm renders a storage system unnecessary, in this particular case study.

Figure 9 illustrates that despite the fact that both algorithms provide the energy required by the load, the control algorithm provides the interrupted loads in a cost-effective manner, thereby reducing or eliminating the energy storage system, provided that the hybrid resources are appropriately sized. This algorithm results in a reduction of 10 percent in the cost of TAC and maintenance and operating expenses within the storage system, as depicted in Table 3.

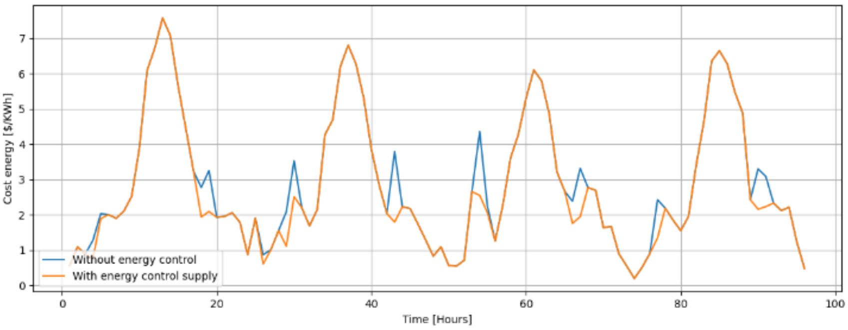


Fig. 9. Uncontrolled battery power dispatch.

Table 3. Parameters values and costs.

Cost Component	Before Implementation ($)	After Implementation ($)
Fixed cost PV	$ 80	$ 80
Fixed cost WT	$ 200	$ 200
Fixed cost BS	$ 176	$ 0.00
Variable cost PV	883 $/kW	883 $/kW
Variable cost WT	1,350 $/kw	1,350 $/kw
Variable cost BS	260 $/kW	$ 0.00
Operating and maintenance cost per PV unit	$ 0.000003	$ 0.03
Operating and maintenance cost per WT unit	$ 0.03	$ 0.03
Operating and maintenance cost per BS unit	$ 0.000012	$ 0.00
Total Annual Cost	$ 21,733.83	$ 19560.44

The developed method eliminates the need for a storage system, thereby reducing the investment cost for the integration of a microgrid into the electric power demand system. However, the control system requires the correct sizing of the hybrid generators as well as knowledge of the kWh costs for each element of the system. Similar to the outcomes obtained with this control system, the results aim to determine the structure of a hybrid system that should be more robust and unaffected by distributed parameters. This approach can improve the resilience behavior of the network.

The proposed model in the document takes an economic objective function, which necessitates a comparison of the total cost of the microgrid before and after the implementation of the model. To provide more details and a better representation, a table comparing the total cost before and after the implementation can be created as in Table 3.

The comparison provided in Table 3 offers a comprehensive analysis of the total cost implications associated with the implementation of the proposed economic objective function model in the microgrid system. Prior to the implementation of the model, the capital expenses, operation and maintenance expenses, energy expenses, and revenues from energy sales are outlined to reflect the financial landscape of the microgrid. After the model has been integrated, a new set of values for each cost component is presented, showcasing the potential changes in the total annual cost of the microgrid. This comparison table is a valuable tool for evaluating the economic impact of the proposed model, highlighting any cost reductions or increases that may arise from its implementation, and providing a clear and structured representation of the financial implications of adopting the economic objective function in the microgrid.

6. CONCLUSIONS

The proposed control system aims to attain an objective function of determining the dispatch of electric energy in a hybrid system, thereby reducing the annual operational expense. A sufficient dimensioning of the generation systems and the storage system that constitutes the hybrid system has been achieved in the procedure. Additionally, the developed proposal considered the physical and technical conditions of the hybrid system as restrictions. The empirical investigation has demonstrated the effectiveness of the proposed methodology. The decrease in annual operating expenses of the system, coupled with the evidence indicating its viability, indicate that the implementation of an energy storage system in an alternating current microgrid is not necessary, as its implementation would result in an increase in annual operating expenses.

The methodology developed in this article will be extended to address the problems of stochastic costs and parameter variation, among others, in future work. The proposed methods will combine mathematical and data science techniques with computationally efficient and dynamic programming techniques. Besides achieving technical and environmental objectives, we also strive to achieve.

This paper presents a detailed overview of the development of a control system for hybrid energy systems, with a focus on energy management and economic performance optimization. Through the integration of renewable energy sources and energy storage systems, it highlights the importance of implementing a control system to efficiently manage the dynamic demand for electricity in various sectors such as industrial, commercial, transportation and residential. The study proposes a strategic operational approach that defines an operation policy for an energy management system based on hybrid systems. It analyzes the dynamic behavior of energy demand, energy purchase and sale prices in the market, and unit energy prices resulting from the implementation of the hybrid system. The findings highlight that the incorporation of a control system in energy management is crucial for enhancing the economic performance of energy supply. Furthermore, the evaluation of the impact of hybrid system operation involves determining the timing and magnitude of energy supply from both generated and stored sources. The results demonstrate that the proposed control provides benefits and convenience for both flexible and inflexible loads. The importance of this integrated control approach for hybrid power systems is highlighted in optimizing economic performance and operational efficiency.

Furthermore, the article discusses the importance of developing advanced control systems for energy management in microgrid environments, with a focus on the integration of renewable energy sources and storage systems. Effective control strategies not only improve economic performance, but also contribute to optimal energy management and meet diverse load requirements. They also promote long-term energy sustainability.

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CONFLICTS OF INTERESTS

Conflict of Interest. The authors declare that they have no conflicts of interest.
Human and Animal Rights and Informed Consent. This article does not contain any studies with human oranimal subjects performed by any of the authors.

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