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Abstract—Multi-energy microgrids (MEMGs) have emerged as an effective solution for reducing greenhouse gas emissions. These systems leverage the coordination of multiple energy vectors to enhance efficiency and achieve greater independence from the main grid. This paper introduces a dynamic fuzzy-logic energy management system (EMS) designed for a MEMG that encompasses gas and electricity energy vectors. The thermal network of the MEMG comprises a gas boiler, an electric boiler, and a heat load. In parallel, the electrical network consists of a photovoltaic (PV) system, a battery energy storage system, an electric load, and a connection with the grid. The EMS plays a crucial role in evaluating the PV power generation and electric demand, and it adjusts the water temperature in the electric boiler to minimize reliance on the local grid. To evaluate the effectiveness of the MEMG and EMS, a simulation spanning 4.5 hours was conducted under various operating conditions for sun irradiance, heat, water, and electric demand. The results demonstrate the capability of the fuzzy-logic based EMS to reduce the dependence on the local grid, thereby showcasing the suitability of this approach in MEMGs.

Keywords—Multi-energy microgrids, fuzzy-logic, energy management system, PV system, battery bank, thermal vector.

I. Introduction

The increasing focus on reducing greenhouse gas emissions has led to the growth of distributed generation through microgrids (MGs) that utilize renewable sources like solar or wind energy. To mitigate the fluctuations in these sources, energy storage systems (ESSs) are often employed. Taking it a step further, some MGs incorporate multiple energy vectors, such as gas or hydrogen, alongside electricity [1]. When these energy vectors complement each other to enhance the efficiency of the MG, this is referred to as a multi-energy microgrid (MEMG) [2].

MEMGs incorporate various conversion units such as gas-to-power, power-to-gas, hydrogen-to-power, or power-to-hydrogen, to cater to both electrical and thermal loads, as well as store energy in hydrogen, electrical, or thermal systems. As a result, MEMGs can have diverse input and output energy vectors, with interconnected relationships between generation sources and energy storage units [3].

The primary focus of MEMG development has been on smaller-scale applications such as buildings, communities, and industries that rely heavily on electricity and gas. In these scenarios, clean energy sources, specifically renewables for electrical energy and natural gas for thermal energy, are commonly employed. The implementation of distributed generation with interconnected MEMGs enhances the stability and efficiency of the overall system, allowing for local generation using various renewable energy technologies alongside different ESSs [2]. Additionally, MEMGs and distributed generation offer significant flexibility, enabling the smoothing of fluctuations in generation and consumption within the MEMGs themselves, as well as with their connection to the distribution network.

The configuration of an MEMG depends on its intended application. These units include: a) energy sources, commonly renewable energy technologies like photovoltaic (PV) systems and/or wind turbines; b) ESSs such as electrical batteries, supercapacitors, cooling/heat storage units, or hydrogen tanks; c) energy conversion systems like electrolyzers, fuel cells, heat pumps, electric chillers, or natural gas power plants (cogeneration); d) transmission systems encompassing electrical, natural gas, or hydrogen networks; and e) final consumption units for electrical, thermal, or hydrogen loads [4].

Effective modeling of MEMGs is crucial for designing and evaluating their control, stability, and coordinated operations involving different energy vectors. MEMG models can be approached from two perspectives. The first one is considering an "outside" viewpoint, where the MEMG is considered as a single entity interacting with the external world. This perspective enables an input-output analysis, which is valuable for static applications such as power system operation and planning [4].

The second approach in modeling MEMGs is the 'inside' viewpoint, which focuses on their control and operation. In this approach, the models need to take into consideration the non-linearities of energy conversion and transitory states. One of the main challenges in doing so is the difference in the response speeds among the energy vectors. Hence, it is crucial to develop dynamic models of MEMGs to guarantee their feasibility and computational efficiency. In the existing literature, numerous studies have developed intricate modelling of the dynamics of each MG module and implemented control algorithms to enhance their performance according to specific needs.

Using the above-described models, EMS formulates appropriate control actions that lead the MEMG to the desired operating state. A static EMS is based on pre-established strategies that are not adaptable to immediate changes in energy requirements. These strategies are typically based on databases or empirical data. A static EMS adheres to a predetermined algorithm to achieve a particular target. On the other hand, a dynamic EMS incorporates instantaneous

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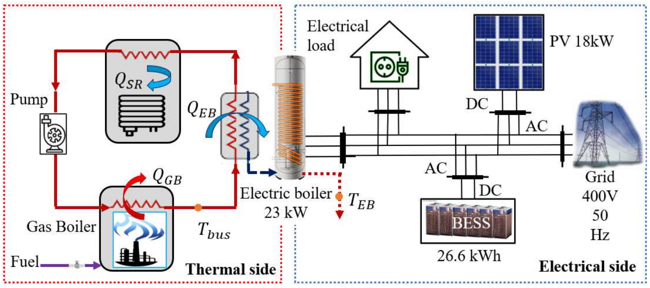

Fig.1 . Schematic diagram of the electrical-thermal MEMG.

monitoring and control of energy consumption considering temporary operating modes. It has the ability to react to real-time fluctuations in demand by adjusting production levels, taking into account factors like weather conditions and the charge status of ESSs.

Recently, there has been growing interest in new EMS algorithms, including fuzzy logic, neural networks, genetic algorithms, and model predictive control. Of the different control strategies mentioned above, fuzzy logic systems have found application in diverse fields because they can adapt to complex systems, as the MEMG proposed in this paper. Other intelligent controllers require historical data, unlike fuzzy systems, which do not rely on that. Furthermore, the system does not need to be linearized to implement fuzzy logic control, which makes it easier its implementation in dynamic models.

For instance, reference [5] proposed an intelligent offline meta-heuristic optimization algorithm based on fuzzy-logic for a hybrid MEMG. However, this algorithm did not consider the transient states of the system. The results demonstrated the effectiveness of an optimal fuzzy inference system that adopted predicted information over a specific time period. A fuzzy-logic EMS was presented in [6] for a residential electrothermal microgrid in a static frame. This EMS was based on the forecast of the electrical and thermal power balances. The same authors implemented in [7] a fuzzy EMS based on power forecasting, using real-data input, to improve the grid power profile and minimize the power fluctuation.

Previous research on MEMGs has primarily focused on static analysis over long timeframes, primarily for economic or power flow optimization purposes, as evidenced by previous studies [8,9,10]. However, there are a limited number of papers that have addressed the dynamic modelling and control of MEMGs, with only a few considering timescales of a few seconds or hours [11,12]. This paper aims to contribute new approaches for the dynamic study and control of MEMGs, with the objective of enabling real-time control that takes into account the dynamics of the MEMG components. The proposed approach is a dynamic fuzzy-logic based EMS, which allows for the control of the MEMG in different weather conditions and varying thermal/electrical loads, with the ultimate goal of reducing reliance on the main grid to power the loads.

The focus of this paper is on a MEMG that combines heat and electricity. To effectively operate the MEMG and meet the thermal and electric load requirements while minimizing reliance on the grid, a novel dynamic EMS based on fuzzy-logic is presented. The novelty lies in determining the operating mode of the electric and gas boiler, as well as the power to be managed by the BESS, depending on the renewable power available at the moment. The main objective of this approach is to avoid consuming energy from the main grid, and thus achieve a self-sufficient MEMG. The proposed EMS takes into account the electricity demand of the MEMG and the consumption of the electric boiler. Furthermore, this EMS considers factors such as PV generation, available power in the BESS, and the control of the state-of-charge (SOC) of the BESS to ensure a safe operation and maximize its lifespan.

II. Multi-Energy Microgrid under Study

Fig. 1 illustrates the scheme of the studied MEMG. The MEMG is composed of a PV power plant, a BESS, an electrical load, and a thermal load, all of which are connected to the three-phase grid. The PV power plant and BESS aim to supply as much electrical load as possible without relying on the grid connection. The PV power plant has a capacity of 18 kW, comprising six parallel strings with 10 series-connected modules per string. Each string can extract a maximum power of 300 W, where 37.5 V is the voltage at maximum power point per string. A 'perturb and observe' algorithm is employed to implement the maximum power point tracking (MPPT) strategy. To address the situation where the electrical and thermal load capacities surpass the capacity of PV generation, a lithium-ion BESS is integrated into the system. It has a power capacity of 26.6 kWh and a rated voltage of 345V. It serves as a backup to support the PV power plant during periods of insufficient energy production or when additional energy beyond the installed capacity is required.

The MEMG model takes into account the dynamic modeling of thermal components, such as the gas boiler, pump, and a 300-liter electric boiler. The electric boiler has a capacity of 23 kW and supplies a variable thermal load demand. To achieve this, the thermal components of the MEMG under study were dynamically modeled using the CARNOT toolbox extension in MATLAB Simulink [13], which incorporates thermodynamic and energy engineering models [14,15]. It provides a library of typical components found in thermal systems, represented by blocksets equivalent to commonly used components. Further details regarding the coordination between electrical and thermal systems, as well as the specific elements related to thermal loads, will be discussed in the following sections.

A. *Gas Boiler*

In this model, the heat provided is introduced into the combustion chamber of the boiler. To account for interdependent conditions, a multi-node model is implemented on the furnace water side [16]. The dynamic behavior can be modeled according to Eq. (1) in the frequency domain. It represents the thermal balance, taking into account the heat provided by the gas, the thermal losses with the ambient and the thermal increment in the gas [14]. Table I collects the thermal parameters of the electric and gas boiler, employed in Eqs. (1) and (2).

B. *Electric Boiler*

In the case of an electric boiler, the received electricity is converted into heat. The primary components of an electric boiler include tubular heating elements, insulation layers, and exterior bodies. The electrical power supplied from the electrical side of the MEMG is responsible for heating the introduced water mass flow. Eq. (2) represents the thermal balance for the electric boiler in the frequency domain. Furthermore, the model considers ambient thermal losses by

$$T_{bus} = \frac{UA \cdot \frac{1}{N}}{\left(m \cdot \frac{c}{N}\right) \cdot s + \left(UA \cdot \frac{1}{N} + \dot{m} \cdot c_f\right)} \cdot T_{amb} + \frac{\dot{m} \cdot c_f}{\left(m \cdot \frac{c}{N}\right) \cdot s + \left(UA \cdot \frac{1}{N} + \dot{m} \cdot c_f\right)} \cdot T_{in} + \frac{\frac{1}{N}}{\left(m \cdot \frac{c}{N}\right) \cdot s + \left(UA \cdot \frac{1}{N} + \dot{m} \cdot c_f\right)} \cdot Q_{GB} \tag{1}$$

$$T_{EB} = \frac{UA}{(mc_p) \cdot s + (UA + \dot{m} \cdot c_p)} \cdot T_{amb} + \frac{\dot{m} \cdot c_p}{(mc_p) \cdot s + (UA + \dot{m} \cdot c_p)} \cdot T_{in} + \frac{1}{(mc_p) \cdot s + (UA + \dot{m} \cdot c_p)} \cdot P_{EB} \tag{2}$$

establishing a thermal node with an initial temperature that is the same as the ambient temperature [15,17].

C. PV Power Plant

The PV system implementation described in [18] is selected due to its demonstrated accuracy and simplicity. This particular model utilizes irradiance and temperature as inputs and produces the I-V characteristics as outputs. It comprises a diode, a controlled current source, and two resistances (one in series R_S and one in parallel R_{sh}). According to [18], the expression for the output current of the PV system (I_{PV}) is as follows:

$$I_{PV} = I_L - I_{sat}\left(e^{\frac{q(V_{PV} + I_{PV} R_S)}{nKT_{PV}}}\right) - (V_{PV} + I_{PV} R_S)/\, R_{sh} \tag{3}$$

where I_L depicts the light current, I_{sat} is the diode reverse saturation current, V_{PV} denotes the PV voltage and T_{PV} is the cell temperature. It is important to highlight that the photovoltaic (PV) energy facility employs the maximum power point tracking (MPPT) strategy based on the Perturb & Observe (P&O) algorithm. This methodology effectively exploits both PV voltage and current to determine the optimal voltage under varying operational conditions. Specifically, the P&O algorithm for MPPT involves iteratively adjusting the PV voltage and monitoring the corresponding output power. In light of these observations, the P&O technique calculates the necessary adjustment direction to converge towards the maximum power point (MPP), ensuring maximum power extraction from the PV system.

D. BESS Model

The BESS model employed in this study is derived from the model available in the SimPowerSystems toolbox of Simulink [19]. Modifications have been made to ensure precise representation of the V-I and V-SOC curves, as well as the dynamic response of the device, using the information provided in the datasheets. The model consists of a variable voltage source and a series resistance:

$$V_{BESS} = E_{BESS} - I_{BESS} \cdot R_{int} \tag{4}$$

where V_{BESS} denotes the BESS voltage, E_{BESS} the open circuit voltage, I_{BESS} represents the BESS current and R_{int} the internal resistance.

TABLE I. ELECTRIC AND THERMODYNAMIC PARAMETERS.

Symbol	Parameter	Unit
c	Heat capacity boiler	J/(kg·K)
c_f	Heat capacity of fluid	J/(kg·K)
c_p	Heat capacity of fluid (constant pressure)	J/(kg·K)
E_{BESS}^{nom}	BESS rated capacity	Wh
m	Mass of the boiler	kg
mcp	Thermal capacity of the boiler	J/K
$\dot{m}$	Mass flow rate	Kg/s
n	Number of PV modules	-
N	Number of nodes	-
P_{EB}	Electric boiler power	W
$P_{BESS,char}^{max}$	Maximum BESS power in charging mode	W
$P_{BESS,dis}^{max}$	Maximum BESS power in discharging mode	W
Q_{EB}	Heat power of the boiler	W
T_{amb}	Ambient temperature	ºC
T_{in}, T_{bus}	Input and Bus temperature	ºC
UA	Heat loss coefficient to ambient	W/K

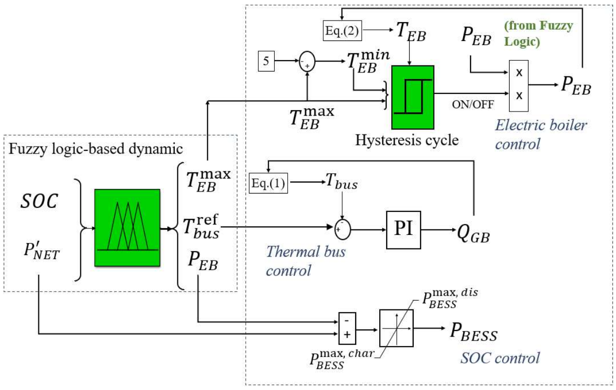

Fig. 2. Overall energy management system based on fuzzy logic.

III. CONTROL SYSTEM AND EMS

A new control system and an EMS based on fuzzy logic are presented in Fig.2 for the MEMG shown in section II. The primary goal of the EMS is to synchronize the operation of the gas and electric boilers in response to the production of the PV power plant, BESS, and the demand for electric load. By doing so, the MEMG functions as an independent MG, capable of meeting the thermal and electric load requirements without relying on a local grid. The control system consists of various subsystems, which will be described in the following sections.

A. System Operation

The operation of the heating load can be summarized as follows. Initially, electrical pumps pressurize the water within the building supply pipe. Next, a gas boiler warms the water. The heated water then enters a thermal bus that connects the gas and electric boilers to the thermal loads. An electric boiler further heats the water within the thermal bus to the required temperature for the bus. As the heating process progresses, the water flow and demand for hot water may fluctuate, necessitating the regulation of water temperature and the corresponding electrical power. To achieve this, a proportional-integral (PI) controller is employed to adjust the temperature difference between the thermal bus and gas boiler.

B. Thermal Bus Control

The thermal bus control subsystem has the task of regulating the temperature of the thermal bus (T_{bus}) to the desired reference value (T_{bus}^{ref}). To achieve this, a gas boiler is used to increase the temperature of the incoming water and manage the bus based on the demand for underfloor heating and hot water usage. A PI controller modulates the thermal power of the gas boiler (P_{GB}) to achieve the desired bus temperature.

C. Electric Boiler Temperature Control

The electric boiler temperature control subsystem is responsible for managing the output temperature of the electric boiler (T_{EB}) based on the operating mode determined by the EMS. A hysteresis control cycle is employed to regulate the temperature effectively. To accomplish this, the fuzzy-logic determines the operation mode of the electric boiler. The electric boiler is then activated until it reaches the upper threshold and deactivated when it reaches the lower threshold. This approach ensures temperature control without constantly supplying power to the electric boiler.

D. Dynamic Fuzzy Logic EMS

As mentioned earlier, the EMS developed for the MEMG is illustrated in Fig. 2. It relies on a fuzzy logic framework. This control based on fuzzy logic generates T_{max}^{EB} (turn-off temperature of the electric boiler), P_{EB} (power to be absorbed by the boiler) and T_{bus}. The proposed EMS relies on the gross net power ($P_{NET}^{'}$) and the SOC of the BESS as inputs of the EMS. Consequently, the control system comprises two inputs

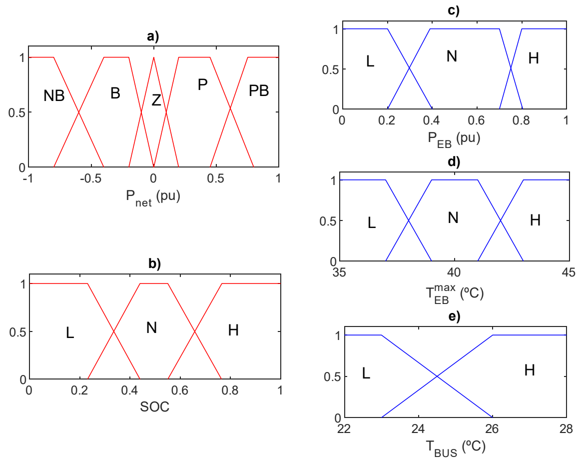

Fig. 3. Membership functions: a) Gross net power (P_{NET}'), b) BES SOC, c) electric boiler power (P_{EB}), d) electric boiler turn-off temperature (T_{max}^{EB}), and e) temperature in the thermal bus (T_{bus}).

and three outputs.

$P_{NET}^{'}$ is defined in Eq. (5). Furthermore, the net power (P_{NET}) can also be calculated as Eq. (6), which denotes the power that the BESS must manages. The BESS power is calculated as a function of Eq. (6), and is constrained based on its current SOC, as described in Eq. (7) and (8). In this paper SOC_{max} = 90% is the maximum limit for charging mode, and SOC_{min} = 30% is the discharging threshold. Additionally, the turn on temperature of the electric boiler (T_{EB}^{min}) is set to be four Celsius degrees lower than T_{EB}^{max}.

$$P_{NET}' = P_{PV} - P_{LOAD} \quad (5)$$

$$P_{NET} = P_{BESS} = P_{NET}^{'} - P_{EB} \quad (6)$$

$$P_{BESS,dis}^{max} = min\left(P_{BESS}^{max}, \frac{E_{BESS}^{nom}}{\Delta t} \cdot \left(\frac{SOC - SOC_{min}}{100}\right)\right) \quad (7)$$

$$P_{BESS,ch}^{max} = min\left(P_{BESS}^{max}, \frac{E_{BESS}^{nom}}{\Delta t} \cdot \left(\frac{SOC_{max} - SOC}{100}\right)\right) \quad (8)$$

With regards to the membership functions (MFs), five are employed to define P_{NET}' (NB, N, Z, P, PB) and three for T_{bus}^{ref}, SOC, T_{max}^{EB} and P_{EB}, as illustrated in Fig. 3. The system behavior is defined by 15 rules (Table 2), employing a Mamdani-type inference method. Mamdani-type has been selected because it is easy to implement, knowing the behavior of the system. It has also highly flexible and can handles nonlinear systems. Its adaptability to new data or changes in the system makes it suitable for dynamic approach, such as the one proposed in this paper. Furthermore, Mamdani inference method can handle variations and uncertainties in input data, and does not require historical data for training [20]. It is important to note that the primary objective of the EMS is to maximize the utilization of renewable energy, particularly from the PV system, to heat the water in the electric boiler, and consequently, decreasing the dependence on the grid.

The use of fuzzy logics allows the electric boiler to operate over a wide range of temperatures. Because T_{max}^{EB} and T_{min}^{EB} are controlled in each moment, there are multiples operating modes for the electric boiler, and it is not limited to low, normal or high temperature-operating modes. Fuzzy logic avoids an all-or-nothing consumption, because P_{EB} varies depending on P_{NET}' and SOC, and is not fixed to its rated power. When P_{NET}' is positive, the electric boiler becomes the primary heat source, and the BESS is charged until it reaches SOC_{max}. If the SOC reaches SOC_{max}, the surplus energy is delivered to the local grid. However, if P_{NET}' is negative and the SOC is low, the available P_{EB} decreases, and the BESS power is limited. In this situation, the local grid provides the required energy to fulfill the demand. This operating mode enables a more intelligent energy use and lower consumption.

IV. Results and Discussion

This section evaluates the performance and effectiveness of the proposed MEMG and fuzzy-logic-based EMS using MATLAB/Simulink. The MEMG inputs are presented in Table 3. They consist of the water flow ($\dot{m}$) profile demand,

		P_{NET}'														
		NB			N			Z			P			PB		
		P_{EB}^{pu}	T_{EB}^{max}	T_{bus}	P_{EB}^{pu}	T_{EB}^{max}	T_{bus}	P_{EB}^{pu}	T_{EB}^{max}	T_{bus}	P_{EB}^{pu}	T_{EB}^{max}	T_{bus}	P_{EB}^{pu}	T_{EB}^{max}	T_{bus}
SOC	**L**	**Z**	**L**	**H**	**Z**	**L**	**H**	**Z**	**N**	**H**	**N**	**N**	**H**	**H**	**N**	**H**
	N	**Z**	**L**	**H**	**N**	**N**	**H**	**N**	**N**	**H**	**N**	**N**	**H**	**H**	**H**	**L**
	H	**N**	**N**	**H**	**N**	**H**	**L**	**H**	**H**	**L**	**H**	**H**	**L**	**H**	**H**	**L**

Table 2. Rule base of the fuzzy logic controller.

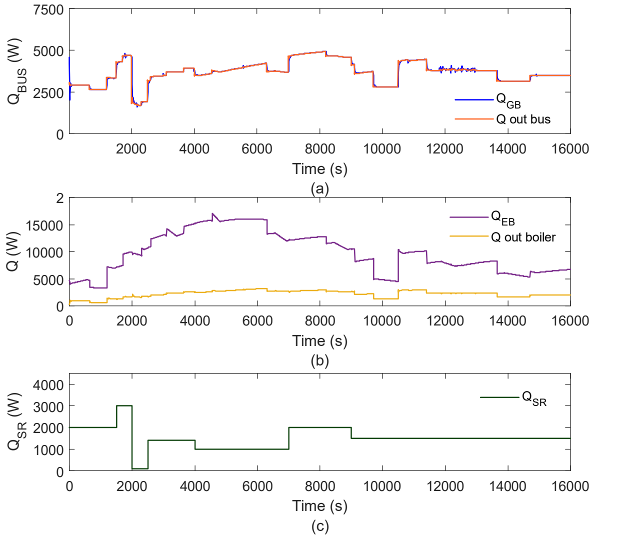

Fig. 4. (a) Thermal power injected by the gas boiler (Q_{GB}), (b) thermal power supplied by the electric boiler (Q_{EB}), and (c) thermal underfloor heating demand (Q_{SR}).

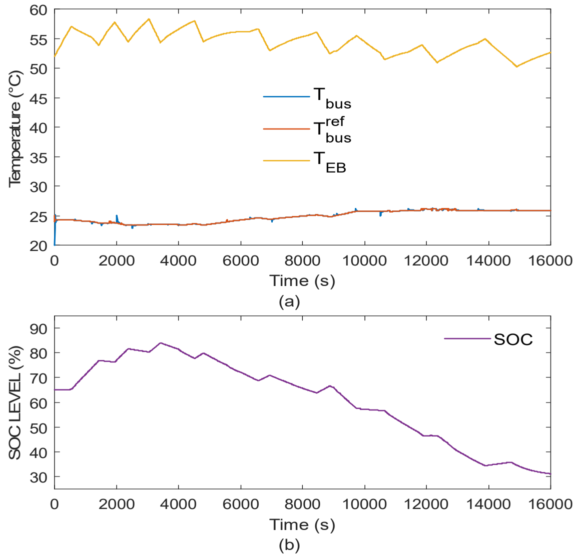

Fig. 5. (a) Measured temperature of thermal bus (T_{bus}), reference temperature of thermal bus (T_{bus}^{ref}) and output temperature of electric boiler (T_{EB}), and (b) State of charge (SOC) of the BESS.

the thermal heat of the underfloor heating demand (Q_{SR}) and the irradiances of the PV power plant (I_{PV}). The initial T_{bus} is set at 24ºC and the initial T_{EB} is set at 54ºC.

Fig. 4 shows the thermal power control performance. The gas boiler is responsible for maintaining the power balance under variations in water consumption and heat demand load. Fig. 4a illustrates the thermal power injected into the thermal bus by the gas boiler (Q_{GB}). This aligns with the thermal power extracted from the bus ($Q_{out,bus}$), which is the

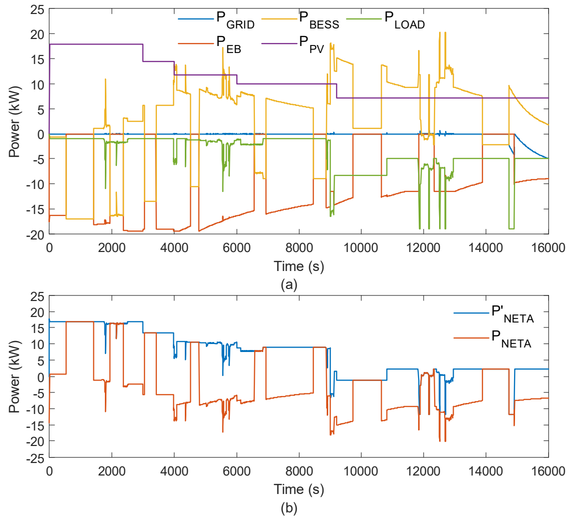

Fig. 6. (a) Electric power balance for the MEMG, and (b) gross net power (P'_{NET}) and net power (P_{NET}).

combination of Q_{SR} and the heating output from the thermal bus ($Q_{out,boiler}$). Fig. 4b indicates the heating power provided by the electric boiler (Q_{EB}) to heat the water in accordance with the operating conditions, along with the heating output from the boiler via the thermal bus. Lastly, Fig. 4c represents the demand for underfloor heating Q_{SR}. The temperature of the thermal bus (T_{bus}) and its reference value (T_{bus}^{ref}) and the electric boiler temperature (T_{EB}) are shown in Fig. 5a. T_{EB} is dynamically controlled by the fuzzy-logic based EMS taking into account P'_{NET} and the SOC of the BESS. On one hand, the operating principle of the electric boiler is regulated by a hysteresis cycle that controls its switching on and off between an upper (T_{max}^{EB}) and lower (T_{min}^{EB}) temperature limits (as discussed in Section III-C).

In Fig. 5a, a high temperature mode for the electric boiler owing to a high PV power (P_{PV}) is observed from 0 to 6000 s. When T_{EB} reaches T_{max}^{EB}, the electric boiler is turned off and T_{EB} starts to decrease until it reaches T_{min}^{EB}. From 6000 to 9000 s, T_{max}^{EB} is decreased as P_{PV} is reduced and therefore, the fuzzy-logic limits T_{max}^{EB}. This situation is maintained for the remainder of the simulation, where P_{PV} has a low value and SOC is decreasing, therefore T_{max}^{EB} continues to decrease.

On the other hand, T_{bus} is controlled by the gas boiler and complemented with T_{EB}. This means that when the fuzzy-logic sets a high value for T_{max}^{EB}, T_{bus} is controlled in a normal range and the heat power is majorly supplied by the electric boiler. However, when the fuzzy-logic sets a low value for T_{max}^{EB}, T_{bus} is incremented and the gas boiler provides more heat power.

Fig. 5b illustrates the SOC control of the BESS. Between 0 and 3500s, the BESS functions in charging mode as P_{NET} is positive. At 3500 s, there is an increase in the electric boiler

Time (s)	650	1200	1700	2300	2600	3100	3650	4550	6300	8200	9100	9700	10500	11400	13650	14700
Water consumption (kg/s)	0.035	0.025	0.055	0.07	0.09	0.1	0.11	0.13	0.15	0.13	0.07	0.04	0.09	0.07	0.10	0.08
Irradiation (W/m^2)	950	950	950	950	950	800	800	650	120	120	140	140	140	140	140	140
Underfloor heating (W)	2000	2000	3000	100	1400	1400	1400	1000	1000	2000	1500	1500	1500	1500	1500	1500

Table 3. MEMG operating parameters.

demand, causing P_{NET} to be less than zero, and the BESS discharges to avoid drawing energy from the grid.

This aligns with the primary objective of the fuzzy-logic EMS presented earlier, which aims to minimize reliance on the main grid to fulfill energy demands.

Fig. 6a shows the electric power balance for the MEMG, including the PV power plant, BESS, electric boiler and electric load demands. As shown, the BESS smoothens out the fluctuations of the PV generator. Furthermore, the peak values of the loads must be assumed by the BESS, instead of the main grid. Finally, the values of P'_{NET} and P_{NET} are represented in Fig. 6b. In Fig. 6a, from 0 to 1800 s, P_{PV} has a high value and P_{NET} is greater than zero. Thereby, P_{EB} is close to the rated power and the BESS is charged. At 3500 s, P_{PV} is reduced and the BESS changes its operation mode to discharge mode to fulfill the peak demand. After 4500 s, P_{EB} is reduced in accordance with the decrease in P_{PV} and also P'_{NET} . At 14,500 s, the SOC is close to the limit for discharging mode (30%) and the P_{BESS}^{max} available is limited. This is why a part of the electrical load must be taken over by the main grid. From 15,000 s, the power consumed by the grid (P_{grid}) increases as BESS power decreases. The results demonstrate that the proposed EMS exhibits a satisfactory response and the MEMG performs adequately, effectively adjusting the operating conditions of the electric and gas boilers to accommodate high, normal, and low temperature conditions.

V. CONCLUSION

Traditionally, the study of MEMGs has focused on a static perspective, typically optimizing the efficiency or costs to control the MEMG based on a long-term horizon. However, the control and energy management of MEMGs from a dynamic perspective has not received sufficient attention. This paper presented a novel fuzzy-logic based EMS in a dynamic control frame for a MEMG. The proposed EMS relies on the available renewable power and the SOC of the BESS to determine the operating mode of the electric and gas boiler and the BESS power, to avoid consuming energy from the main grid. Therefore, the consumption of the electric boiler varies depending on the renewable capacity, and it is not fixed in an all-or-nothing mode, saving energy.

The primary objective of the EMS is to eliminate reliance on the local grid to satisfy the thermal and electric load requirements. The novelty relies on considering the gross net power to calculate the available power that the BESS can manage and the maximum power that the electric boiler can inject for heating. A Li-ion BESS is utilized to mitigate fluctuations in the PV generator to meet consumption peaks without using the main grid. In addition, the SOC of the BESS is controlled within the upper and lower thresholds to ensure secure operation. This limits the maximum and minimum power that the BESS can handle, providing a realistic management.

To evaluate the performance of the MEMG, simulations were conducted under various irradiation levels, water consumption patterns, and electric load profiles over a 16000 s simulation. It dynamically controls the electric and gas boilers based on the available power from the PV power plant and BESS. Furthermore, the dynamic fuzzy-logic EMS successfully handles changes in the PV production, heat and electrical consumption, and reference temperatures, while operating the heat and electrical networks without relying on the grid.

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