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Original citation:

Li, J, Zou, W, Yang, Q & Bao, H 2022, 'Towards net-zero smart system: An power synergy management approach of hydrogen and battery hybrid system with hydrogen safety consideration', Energy Conversion and Management, vol. 263, 115717. https://doi.org/10.1016/j.enconman.2022.115717

DOI 10.1016/j.enconman.2022.115717
ISSN 0196-8904

Publisher: Elsevier

Energy Conversion and Management 263 (2022) 115717

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Towards net-zero smart system: An power synergy management approach of hydrogen and battery hybrid system with hydrogen safety consideration

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ARTICLE INFO

Keywords:
Battery
Fuel Cells
Hydrogen energy storage
Hydrogen safety
Hybrid energy storage system

ABSTRACT

The building system is one of key energy consumption sector in the market, and low-carbon building will make a significant contribution for the worldwide carbon emission reduction. The multiple energy systems including renewable generations, hydrogen energy and energy storage is the perspective answer to the net-zero building system. However, the research gap lies in the synergy power management among the renewable, flexible loads, batteries and hydrogen energy systems, and at the same time, taking the unique characteristic of different energy sectors into account by power managing. This paper proposed the power management approach based on the game theory, by which, the different characteristics of the energy players are described via creating the competing relationship against net-zero emission objective so that to achieve the power synergy. Under the proposed power management method, the hydrogen and battery hybrid system including the fuel cell, electrolyzer and battery is designed and investigated as to unlock the power management regions and control constraints within the building system. Particularly, for the hydrogen system within the hybrid system, the safe and long-lifetime operation is considered respectively by high-efficiency and pressure constraints within the power management. Simulation results show that, providing the same energy storage services for the building system, the fuel cell with the proposed power management method sustains for 9.9 years, much longer than that of equivalent consumption minimization (4.98), model predictive control (4.61) and rule-based method (7.69). Moreover, the maximum tank temperature of the hydrogen tank is reduced by 3.4 K and 2.9 K compared with consumption minimization strategy and model predictive control. Also, the real-time of the proposed power management is verified by a scaled-down experiment platform.

1. Introduction

Accounting for 30% of total energy consumption and 60% of electricity consumption around the world [1], the buildings are becoming one of the key factors for long-term emissions reduction. For example in the US, buildings are responsible for around 38% of the total carbon dioxide emissions, 71% of the total electrical energy consumption, and 39% of the total energy usage [2]. The energy generated with traditional resources such as fossil fuels leads to atmospheric pollution in the short-term period as well as global warming in the long term [3]. Therefore, given the long life cycle of buildings and carbon emissions, emissions reductions in the building sector are critical to the global response to climate change [4]. Thus, smart buildings nowadays have to significantly increase their electricity generation from renewable energy sources. As a kind of sustainable, efficient and clean source, hydrogen energy is attracting increasing attention in recent years [5]. An active combination of the hydrogen energy storage consisting of fuel cell, hydrogen storage tank and electrolyzer together with a complementary battery will help achieve net-zero emissions particularly for the building systems. However, the characteristic of the hydrogen-battery coupling system is quite complicated and directly influences overall performance of net-zero building system (NZB) [6]. How to coordinate the power distribution between the hydrogen energy storage system and battery storage system constitutes the first challenge for a smart power management strategy in such system. Moreover, the lifetime of the fuel cell is highly vulnerable to its operating conditions, and the rapid filling of the hydrogen storage tank with hydrogen produced by the electrolyzer may cause immediate temperature rise threatening hydrogen safety. This

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https://doi.org/10.1016/j.enconman.2022.115717
Received 9 October 2021; Received in revised form 30 April 2022; Accepted 2 May 2022
Available online 12 May 2022

causes another challenge that how to reduce fuel cell degradation and hydrogen storage tank temperature rise in power management strategy. To address the two main challenges, this paper propose a game theory based power synergy management method dealing with the multiple power/energy sources targeting for the net-zero emission of the building systems, benefiting in lifetime extension and hydrogen risk mitigation.

Abbreviation

DOD	depth of discharge
EL	electrolyzer
ECMS	equivalent consumption minimization strategy
EMS	energy management strategy
EV	electric vehicle
FC	fuel cell
HBHS	hydrogen and battery hybrid energy storage
MPC	model predictive control
NZB	net-zero building system
PV	photovoltaic
RBS	rule-based strategy
SOP	state of pressure
SOC	state of charge

1.1. Literature review

Dealing with the optimal power sharing or power management among the multiple energy sectors, the power management strategies have been investigated by many published works. Particular, for the hybrid energy storage systems used in the building system or microgrid, the power management methods can be roughly divided into two categories, i.e., rule-based and optimization-based approaches [7]. Roumila et al. [8] proposed a rule-based strategy (RBS) to control a battery based hybrid energy storage system to ensure electrical production continuity. Hussain et al. [9] proposed a rule-based home power management system with the advantage of significant reductions in the total daily energy consumption. Salpakari et al. [10] proposed cost-optimal rule-based control for buildings to minimize variable electricity cost employing market data on electricity price. Li et al. in [11,12] proposed the hybrid scheme with a new droop control method in the renewable micro-grid and the domestic CHP system with the advantage of extending battery lifetime. The RBS has the advantages of high reliability, easy implementation, and strong robustness [13], however, it lies in engineering experiences of engineers, which may result in poor performance in the building system. Therefore, rule-based approaches are mainly used for building power management in the current market. Nonetheless, the effects of these rules are typically far away from the optimal for smart building design/control objectives, thereby incentivizing alternatives to seek [14]. Thus, rules-based approaches are mainly used for building power management in the current market. Nonetheless, the impact of these rules is often far from optimal for smart building design/control objectives, thereby incentivizing alternatives to seek significant improvements.

To solve this issue, optimization-based approaches can provide more flexible solutions. As a globally optimal algorithm, dynamic programming is often used to develop theoretically optimal power management strategies [15]. The operating expense of a solid oxide cell-based renewable microgrids was minimized by dynamic programming in [16]. However, the computational efficiency of dynamic programming is very low, which dose not meet the requirements for real-time control, especially for dynamic models with multi-objective problem [17]. To explore the possibility of online optimized power management, a model predictive control (MPC)-based power management framework is developed in [18] to optimally control the operation of the clustered microgrids and manage the power flows exchange ensuring a high quality of service. A home power management optimization strategy based on deep Q-learning is proposed by Liu et al. [19] to perform scheduling of home energy appliances with the advantage of reducing electricity consumption, but the hydrogen energy storage is not taken into consideration. In [20], Li et al. proposed a decentralized coordinated control method to improve the system economics. Considering that each unit in hydrogen and battery hybrid system (HBHS) has its own different characteristics [21], game theory (GT) may be able to provide more flexible solutions [22]. The cooperative game theory is applied in [23] to explore the cooperation potential between virtual power plants and demand sides. A cooperative game theory-based multi-agent capacity optimization method for an integrated energy system is proposed by Wang et al. [24] to analyze the benefit interactions among independent operators in decision-making processes.

However, many existing studies on hydrogen and battery hybrid system in buildings or mircogrids power management merely consider how to minimize cost minimization such as hydrogen consumption, without fully taking the performance of HBHS such as hydrogen safety and fuel cell degradation into consideration. Some papers in-vehicle field attempted to establish power management strategies considering fuel cell health. A max–min game theory PMS is proposed by Sun et al. [25] to improve the robustness and the economic performance of the fuel cell hybrid electric vehicles as well as reduce the fuel cell degradation. Hu et al. [17] propose a MPC power management strategy with an explicit consciousness of degradation of both fuel cell and battery systems benefiting in maximizing the economy of a fuel cell vehicle. Similarly, Li et al. [26] proposed a deep Q-network power management for fuel cell vehicle to suppress system degradation.

One major difference between the net-zero building system and other power systems is that both energy scheduling inside the building and between the main grid are under strict constraints. For example, the main grid would expect a fixed pattern of the electricity consumption in the building, which laid more critical requirements on the power management design for the HBHS. For building, suppressing the degradation of fuel cell and keeping the hydrogen energy storage operation in a high-efficiency region are needed to be considered to improved the system economy, which would lead to a mismatch with the energy consumption expected by the main grid. Besides, since the load-demand of the NZB in the off-work period at night has a specific pattern, the energy storage systems especially electrolyzer in the hydrogen energy storage can operate with more flexibility. During the operation of the electrolyzer, the Joule–Thomson effect occurs during the rapid hydrogenation of hydrogen from the electrolyzer to the hydrogen storage tank, resulting in an increase in the temperature of the hydrogen tank [27]. Besides, the hydrogen in the tank is compressed to do work, causing the temperature of the tank to further rise [28], which will lead to the hydrogen storage tank safety risks. However, these issues in the net-zero building with an intelligent power management method have not been fully investigated.

1.2. Motivation and contributions

For the net-zero smart building system, the multiple power/energy system including renewable energy and energy storages is prospective solution. However, the research gap lies in the synergy power management among the renewable energy, flexible loads, batteries and hydrogen energy storage. Especially for the hydrogen system within in the hybrid energy storage system, the safe and long-lifetime operation should be taken into account in the power management. Therefore, targeting for the net-zero emission of the building systems, the motivation of this paper is clear that to fill the research gap within the power synergy management method dealing with the multiple power/energy sources, and the original contributions lies in the following aspects:

- The hydrogen and battery hybrid system including the fuel cell, electrolyzer and battery is designed and investigated to be used in a building system, together with renewable energy and flexible loads, realizing net-zero emission energy system.
- A synergy power management approach is developed based on the max–min game theory dealing with the multiple power competitions

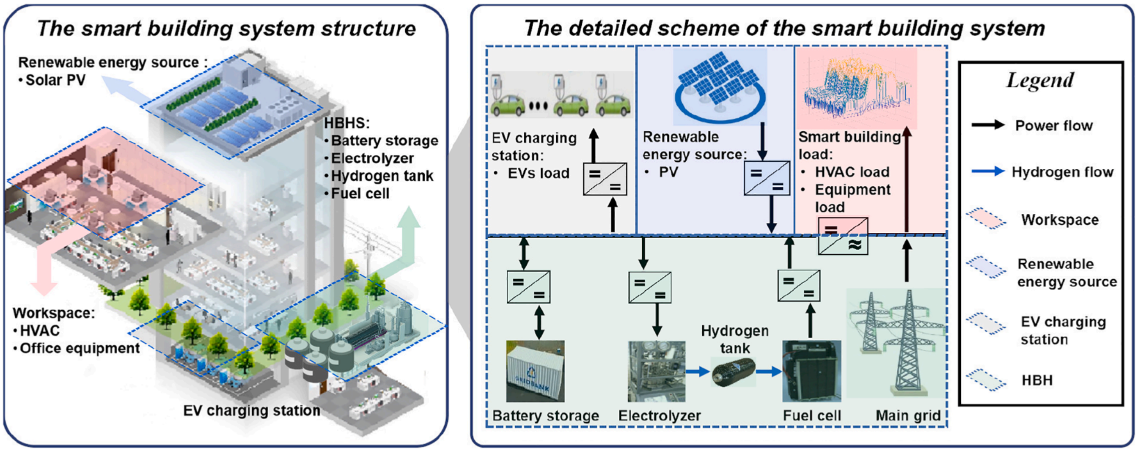
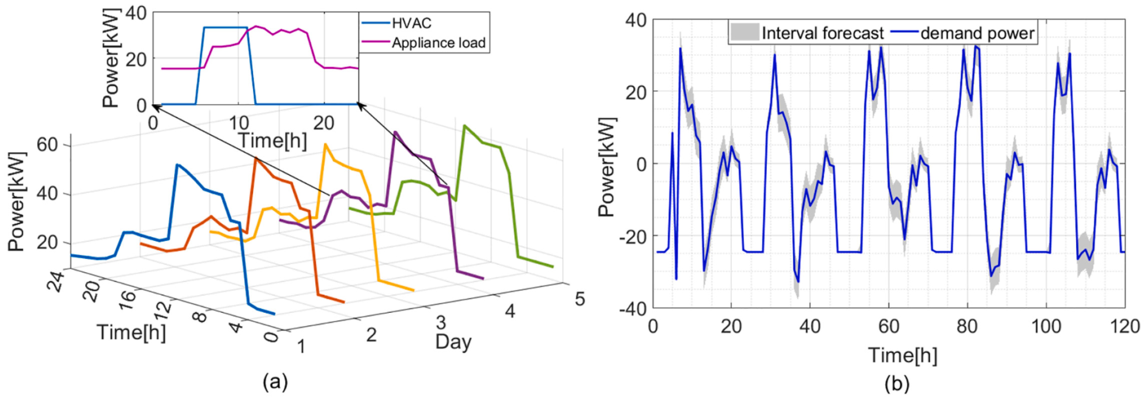


Fig. 1. Structure of net-zero building system.



(a) (b)

Fig. 2. The five days demand power of the building system.

between the hydrogen and battery system, and among the power generations, load demands and energy storage sectors.

- The fuel cell degradation is considered in the proposed power management working as the constrains maintaining the high-efficiency working region of the fuel cell. Also, the hydrogen safety is enhanced by adding the pressure constrains so that to achieve temperature reduction of the hydrogen storage tank.

1.3. *Organization*

This paper is organized as follows. Section 2 introduces the methods of this paper. A test case and experiment presented with results and discussions are introduced in Section 3. Finally, Section 4 provides the conclusions.

2. Method

This section mainly introduces net-zero building system structure, system modeling and game theory energy management. The detailed description is as follows:

2.1. *System description*

In this paper, a smart building with a certain number of distributed energy resources is considered. As shown in Fig. 1, these components include a photovoltaic (PV) system, a hybrid storage system with hydrogen and battery storage system and a number of electric vehicles (EVs) used to pick up employees to work. The hydrogen storage system consists of fuel cell, electrolyzer and hydrogen storage tank. The electrolyzer (EL) is used to convert the surplus of electrical energy to hydrogen and stored in hydrogen storage tank. The fuel cell generates electricity during the peak load period. The EV load is modeled considering deterministic realizations of probabilistic distribution. The building contains heating ventilation and air conditioning load, equipment load and PV generation, which are modeled and validated in [29]. In addition, it is worth noting that smart building systems are connected to the mains grid. The main network only needs to provide stable power to smart building systems at fixed times of the day. Under the control of PV and HBHS, the building system can achieve complete self-sufficiency. Therefore, the total load demand is shown in Fig. 2.

2.2. *Hybrid energy system modeling*

The tank pressure P_{H_2} is a measure of hydrogen content in a container. According to the equation of the state of the ideal gas, the pressure is closely related to hydrogen consumption. So the state of pressure (SOP) can be defined to represent the tank state, the following relationship can be obtained:

$$SOP_{H_2}(t) = SOP_{H_2}(t-1) + \frac{RT}{V}(n_{el} - n_{fc}) \tag{1}$$

where R is the gas constant, T is the mean temperature inside the vessel (assumed here constant and equal to 313K) and V is the overall tank volume (4m^3 in this study), $n_{el}$is the molar mass of hydrogen produced by electrolyzer, n_{fc} molar mass of hydrogen consumed by fuel cell. Due to the feature that the fuel cell and electrolyzer in the system cannot be turned on at the same time, hydrogen produced by the electrolyzer

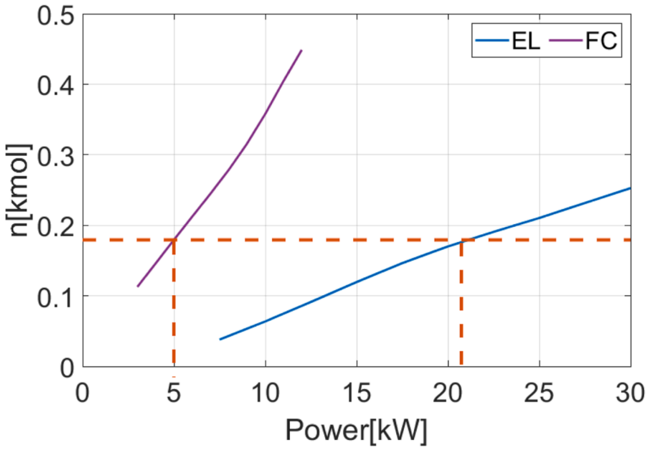


Fig. 3. Fuel cell and electrolyzer efficiency as a function of power.

cannot be used by the fuel cell directly, which must be pressurized and stored in a hydrogen storage tank. The Joule–Thomson effect occurs during the rapid hydrogenation of hydrogen from the electrolyzer to the hydrogen storage tank, resulting in an increase in the temperature of the gas cylinder. Besides, the hydrogen in the hydrogen tank is compressed to do work, causing the temperature of the tank to rise. It is worth noting that the temperature rise of the hydrogen storage tank only occurs during the hydrogenation process. The temperature change caused by the pressure drop of the hydrogen storage tank generated during the normal use phase of the fuel cell is not within the scope of discussion. In order to describe the temperature rise during fast charging, the following assumptions need to be made. The hydrogen temperature inside the tank is evenly distributed during the fast filling process. The energy exchange between the hydrogen storage tank and the pipeline is ignored and the hydrogen flow rate in the pipeline is considered to be constant. The fast charging process is an adiabatic process. Hydrogen is an ideal gas in the fast charging stage. Assume the pressure, temperature, mass of the gas in the tank before inflation are p_1, T_1, m_1, respectively. The pressure, temperature, mass of the gas in the cylinder after inflation are p_2, T_2, m_2, respectively. The pressure and temperature in the hydrogen storage tank are p_0, T_0, respectively. According to the first law of thermodynamics, the heat change in the bottle can be obtained as [30]:

$$Q = m_2 c_{v2} T_2 - m_1 c_{v1} T_1 - (m_2 - m_1) c_p T_0 \tag{2}$$

Where c_{v2} and c_{v1} are equal volume specific heat capacity of hydrogen. $c_p$is the isobaric heat capacity of hydrogen. Q is the energy exchange with the external environment. Due to the fast charging process is an adiabatic process, the Q is equal to zero. Due to the small change of the isovolumetric specific heat capacity of hydrogen, it can be approximated that c_{v2} is equal to c_{v1}. Thus, combine the ideal gas equation of state, the temperature of the hydrogen after fast charging is described as [30]:

$$T_2 = \frac{p_2 T_0 c_p T_1}{(p_2 - p_1) T_1 c_v + p_1 T_0 c_p} = \frac{\gamma p_2 T_0 T_1}{(p_2 - p_1) T_1 + \gamma p_1 T_0} \tag{3}$$

Where $\gamma = \frac{c_p}{c_v}$. For ideal hydrogen gas, $\gamma$is equal to 1.4. Thus, the tank's temperature during the working state of the electrolyzer is characterized by the pressure of the hydrogen storage tank. In the peak period of the power grid, hydrogen can generate electric energy through a fuel cell. n_{fc} is directly related to its output power P_{fc} , and its expression is as follows [31]:

$$n_{fc} = \frac{P_{fc}}{\eta_{fc} LHV_{H_2}} \tag{4}$$

where η_{fc} is the fuel cell efficiency, which takes into account electrochemical, thermodynamic and ancillary losses [31], LHV_{H_2} is the lower heating value of hydrogen (240 MJ/kmol). The electrolyzer produces hydrogen when the power delivered by PV and the main grid is higher than demand. According to the Faraday's law, $n_{el}$is directly related to its power P_{el}[31]:

$$n_{el} = \frac{\eta_{el} P_{el}}{LHV_{H_2}} \tag{5}$$

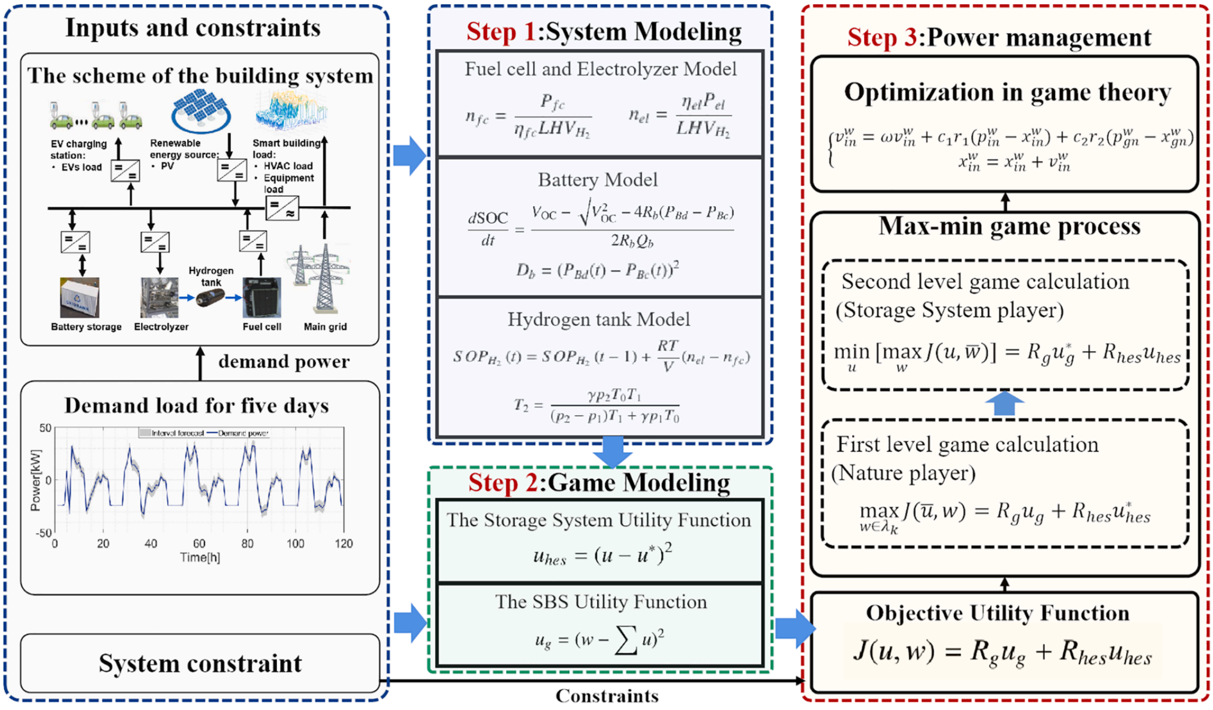


Fig. 4. The overall scheme for power management method.

where η_{el} is the electrolyzer efficiency, which takes into account electrochemical, thermodynamic and ancillary losses [31]. The relationship between power and η_{fc} / η_{el} is shown in Fig. 3. It can be seen that under the same amount of hydrogen, the power of EL is more than four times that of FC, which explains that the rate of hydrogen production cannot keep up with the rate of hydrogen consumption. According to the foregoing studies summary [32], the fuel cell degradation is divided into four categories which are caused by high power, idle condition, star-stop, and power variation. It is significant to carefully control the FC output power to prolong fuel cell lifetime and increase the smart building system economy. This paper adopts a similar approach to [33], so as to account for the effects of the four categories.

The battery is used as the other part of the power source to assist the fuel cell. The battery model can be described by the state of charge (SOC), which is defined as [34]:

$$\frac{dSOC}{dt}=\frac{V_{OC}-\sqrt{V_{OC}^{2}-4R_{b}(P_{Bd}-P_{Bc})}}{2R_{b}Q_{b}} \tag{6}$$

The degradation of the battery can be approximated with a quadratic function, which is adopted extensively in research to simplify the analysis [35]:

$$D_{b}=k_{b}(P_{Bd}(t)-P_{Bc}(t))^{2} \tag{7}$$

where Q_b is the battery nominal capacity, P_{Bc} and $P_{Bd}$are the charging and discharging power, respectively. $R_b$is the equivalent internal resistance, V_{OC} is the open-circuit voltage, $k_b$is the cost parameters of the.

2.3. Game theory

The overall scheme of the power management is shown in Fig. 4. First, according to the aforementioned building system structure, the building model is established. Then, the max–min game theory method is developed to build the game model between the HBHS and net-zero power demand, in which HBHS considers the preferences of each unit and the state of the system to work out an optimized power distribution. Finally, a optimization method is proposed to solve the game model. According to min–max game theory definition, the max–min game problem can be reformulated as the two-level scheme. The game is played repeatedly until the maximum number of games is reached. After obtaining the optimal strategy set, a judgment is made on the system state. If the system is not net-zero and the battery SOC is surplus, then the battery will be used for power compensation and system state updating. As mentioned above, in the proposed approach, the respective preferences of the NZB, the battery and hydrogen storage system, are 1) to achieve the full self-sufficiency of the NZB; 2) to reduce the fuel cell degradation; 3) to make the hydrogen storage system work in a high-efficiency region. Thus, the following quadratic utility functions are defined that reach the minimum values when the preferences are best met. The goal of the power management system is to reduce the hydrogen consumption of the power system and keep the system state near the optimal operating point to ensure the safe operation of the system. Therefore, the cost function is defined as follows:

$$J(u,w)=R_{g}u_{g}+R_{hes}u_{hes} \tag{8}$$

where R_g and R_{hes} represent weight coefficient. w represents the naturally selected strategy set, which represents the feasible interval of the demand load. u is the strategies of players. It can be described as:

$$u=\left[\begin{matrix} p_{fc,k} & p_{el,k} & p_{b,k}\end{matrix}\right] \tag{9}$$

$u_g$is the utility function of the NZB, which represents the self-sufficiency. It can be defined as:

$$u_{g}=(w-\sum u)^{2} \tag{10}$$

The fuel cell utility function is defined to keep the fuel cell working in the high-efficiency range as well as reduce the degradation, which is associated with fuel cell output power. Similar to fuel cell, the utility function of the electrolyzer makes the EL work as efficiently as possible, which is related to electrolyzer power. The battery utility function is defined to reduces battery power fluctuations so as to prolong the battery lifetime. Thus, the hybrid energy system utility function u_{hes}can be described as:

$$u_{hes}=(u-u^{*})^{2} \tag{11}$$

where $u^*$is represent the set value of hybrid energy system states. (such as the fuel cell power is set to the highest efficient point) To ensure the safe operation of the system, the system constraints are as follows:

$$\left\{\begin{array}{lll} p_{b,min}\leqslant & p_{b,k} & \leqslant p_{b,max}\\ p_{el,min}\leqslant & p_{el,k} & \leqslant p_{el,max}\\ p_{fc,min}\leqslant & p_{fc,k} & \leqslant p_{fc,max}\\ soc_{min}\leqslant & soc_{k} & \leqslant soc_{max}\\ sop_{min}\leqslant & sop_{k} & \leqslant sop_{max}\end{array}\right. \tag{12}$$

where $p_{b,min}$and $p_{b,max}$,$p_{el,min}$and $p_{el,max}$,$p_{fc,min}$and $p_{fc,max}$are the minimum and maximum allowable output power of the battery, EL and FC respectively. $soc_{min}$and soc_{min}, $sop_{min}$and $sop_{max}$are minimum and maximum allowable SOC and SOP respectively. Then, according to min–max game theory definition, the max–min game problem can be reformulated as the two-level scheme. It can be described as follows:

$$w^{*}=\underset{u^{*}}{\mathrm{argmax}}J(u^{*},w) \tag{13}$$

$$u^{*}=\underset{w^{*}}{\mathrm{argmin}}J(u,w^{*}) \tag{14}$$

Therefore, the decision process based on the min–max game can be described as follows:

$$u^{*}=\underset{w^{*}(k)}{\mathrm{argmax}}\,\underset{u(k)}{\mathrm{min}}J(u,w^{*}) \tag{15}$$

The first level objective is to select the maximization cost function of the corresponding strategy from the policy set W, while the second level objective is to select the minimization cost function of the corresponding strategy from the policy set U.

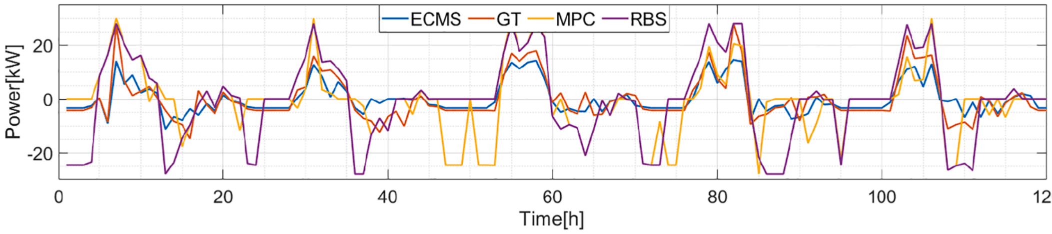


Fig. 5. The battery power distribution with different methods.

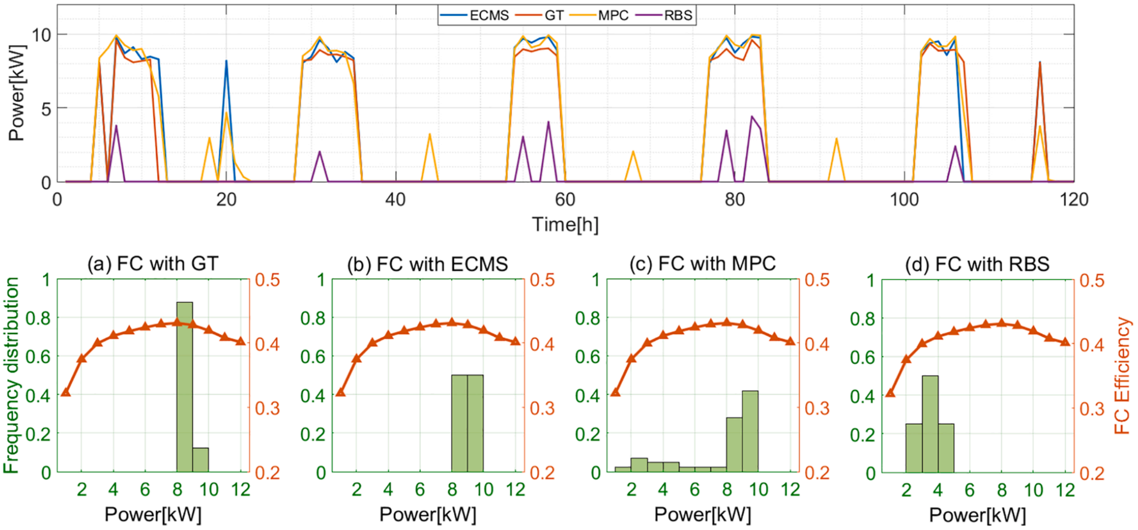


Fig. 6. The fuel cell power distribution and frequency distribution with different methods.

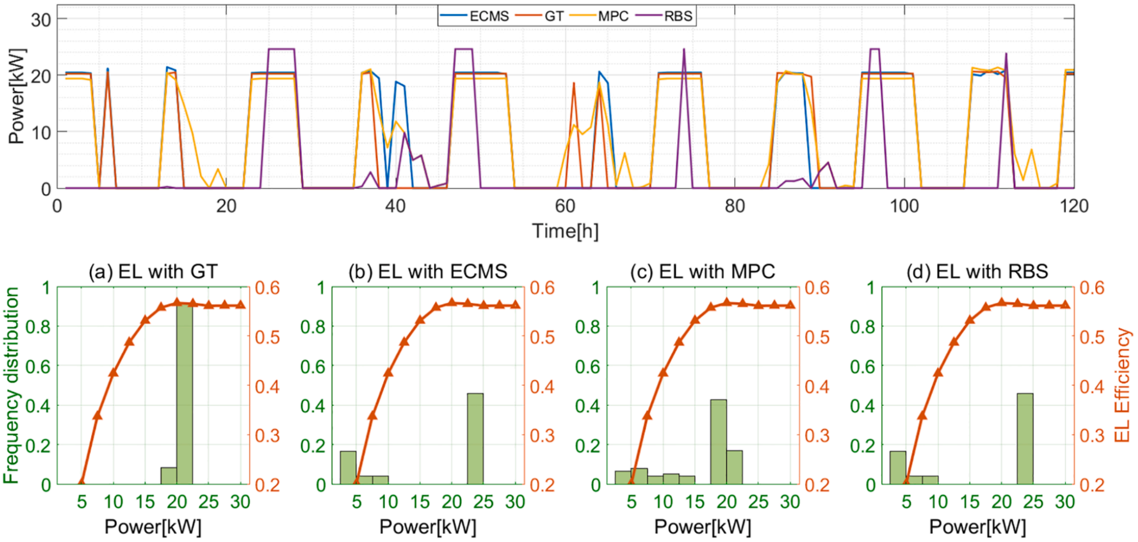


Fig. 7. The electrolyzer power distribution and frequency distribution with different methods.

3. Results and discussions

In this section, the results of HBHS power allocation are summarized and illustrated. The simulation results are presented to demonstrate the performance of the proposed strategy. Moreover, to illustrate the improvement in the HBHS performance of the smart building, the comparisons have been made among the proposed strategy, rule-based strategy (RBS), equivalent consumption minimization strategy (ECMS), and model predictive control (MPC). The rule of the RBS is to give priority to using the battery as the power source in order to avoid frequent use or high-power output use of the fuel cell, so as to protect the fuel cell.

3.1. Simulation and discussions

This part mainly analyzes the simulation results, including the analysis of the power distribution results, the hybrid system lifetime analysis and the analysis of the temperature rise of the hydrogen storage tank.

3.1.1. Power distribution

Fig. 5 shows battery power distribution and the pressure of the hydrogen storage tank. For RBS, its strategy is to reduce the utilization rate of fuel cells by using battery to extend the life of fuel cells. Thus, the battery power fluctuates most violently among the four methods. To evaluate the operation of FC and EL, the power and frequency distribution of the hydrogen storage system with different strategy are shown in Fig. 6 and Fig. 7. FC and EL efficiency varies according to the power, and the maximum efficiency occurs with relatively intermediate power. It is obvious that the operation points of the FC and EL of the GT are distributed in the high-efficiency range and more centralized than other methods. The high load is defined as exceeding 80% of the maximum power of the fuel cell, and less than 20% of the maximum power of the fuel cell is defined as a low load [36]. In Fig. 6(top), it can be seen that the fuel cell high load time with RBS and ECMS is more than that with GT. The fuel cell low load time with RBS is more than with GT. To evaluate the instantaneous fluctuation of fuel cell output power with different methods, the average change rates of the fuel cell output power is calculated. The average change rates under GT, MPC, RBS and ECMS methods are 1.0614 kW/h, 1.1869 kW/h, 0.3861 kW/h and 1.2727 kW/h, respectively. Since the rule of RBS is to reduce the fuel cell power

Table 1
Degradation of fuel cell with different algorithm.

	GT	ECMS	MPC	RBS
$D_{start-stop}$	0.0133%	0.0152%	0.0209%	0.0133%
D_{change}	0.00038%	0.00046%	0.00024%	0.00013%
D_{idle}	0	0	0.0086%	0.0043%
D_{high}	0	0.0118%	0	0
Total	**0.0137%**	**0.0275%**	**0.0298%**	**0.0178%**
Estimated lifetime	**9.99 years**	**4.98 years**	**4.61 years**	**7.69 years**

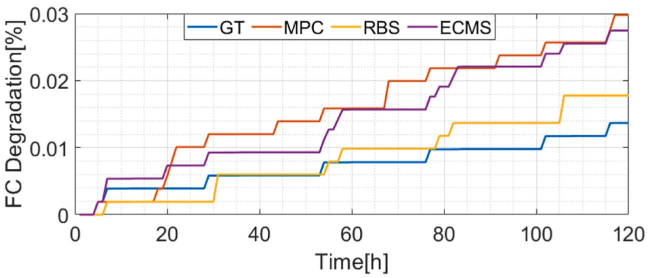


Fig. 8. Fuel cell degradation with different methods.

output to reduce hydrogen consumption, the fuel cell power fluctuation of RBS is minimal, which is not comparable. Among the other three methods, as can be seen, the fuel cell power fluctuation of the proposed method is far less than other methods, which is shown that the proposed method can reduce fuel cell power fluctuations to reduce degradation.

3.1.2. *Lifetime analysis*

The fuel cell degradation with different working conditions are summarized in Table 1. It can be seen from Table 1 that the degradation of the fuel cell mainly comes from power fluctuation and frequent start and stop. The proposed method can minimize fuel cell degradation by reducing start-stop and load change degradation. The fuel cell degradation is shown in Fig. 8. Since the start-stop is the working condition that has the greatest impact on fuel cell degradation, which reduces the lifetime of the fuel cell by 1.9×10^{-3}%. Therefore, each step in Fig. 8 represents a start-stop condition. It is clear that under the GT, the fuel cell degradation is the lowest about 0.0137% among the four methods. For RBS, the battery is the priority that is used to reduce the time of fuel cell high load working condition, however, the time of fuel cell low load working condition is increased, which exacerbates fuel cell degradation. For MPC and ECMS, the time of fuel cell high power output is increased due to lack of battery compensation mechanism, which increases the fuel cell degradation. For GT, the PMS aims to keep the operating point of the fuel cell at the maximum efficiency point, leading that the decision of PMS will be conservative, so the fuel cell prolongs the single working time and reduces the start-stop times, which enables the battery to provide the peak power required in the future. In order to further quantify the fuel cell degradation results, the fuel cell degradation is converted into usable years. The conversion formula is as follows:

$$Year = \frac{Day_{test}}{365 \times D_{total}/10\%} \tag{16}$$

where the $Day_{test}$is simulation time. In this paper, $Day_{test}$is 5 day. $D_{total}$is the total degradation during the simulation. Accroding to the [17], 10% voltage decrease of fuel cell at rated current represents the end of fuel cell lifetime. Then the usable years of fuel cell with the four methods are

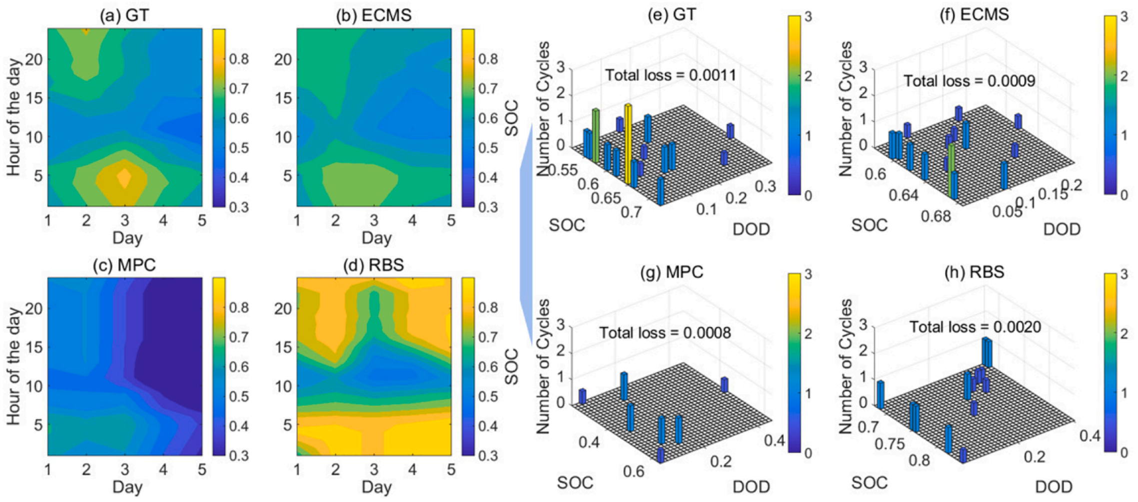


Fig. 9. The spectrum and cycle life of battery under different algorithms.

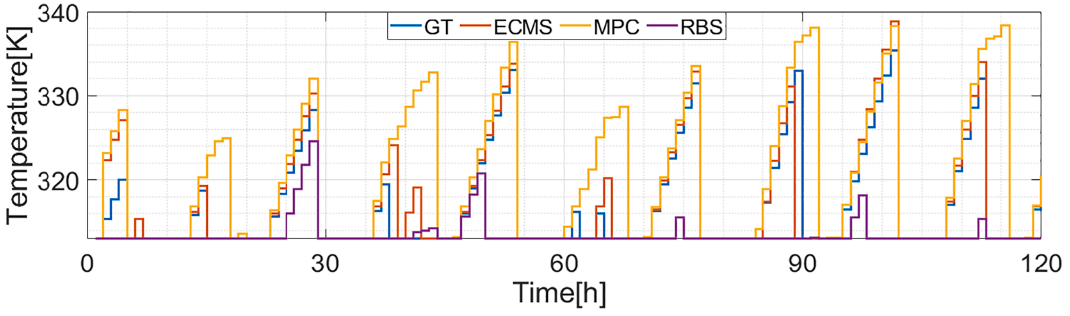


Fig. 10. The temperature change in hydrogen storage tank.

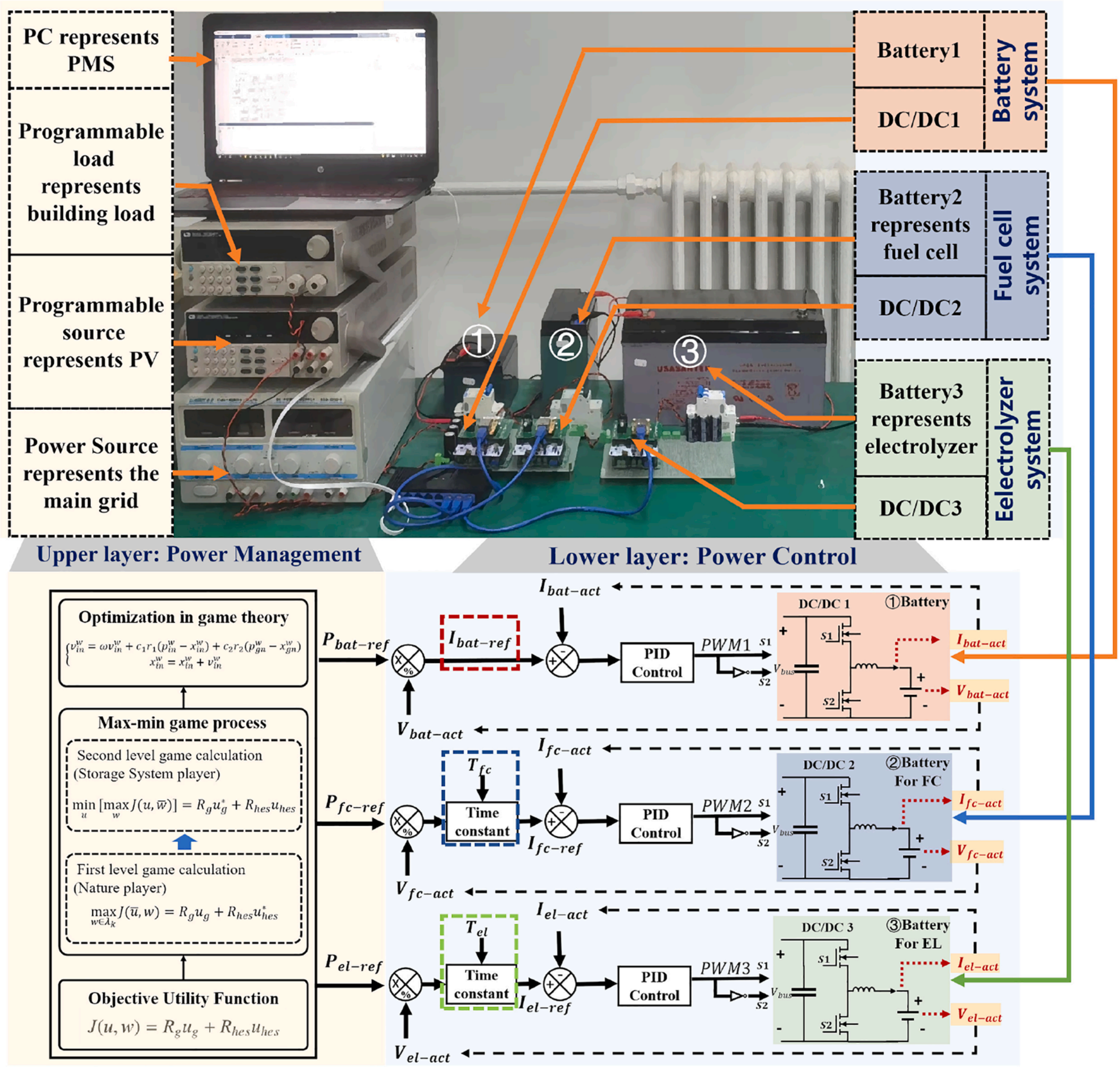


Fig. 11. The structure of the experiment platform and control method.

9.99 years, 4.98 years, 4.61 years, 7.69 years. To analyze the battery degradation, the rainflow method which counts the number of cycles under different deep of discharge (DOD) is used to evaluate the battery lifetime [37]. Fig. 9(a)-(d) shows the spectrum of battery SOC under different methods, where the change of the color means DOD. It can be seen that the color of RBS changes great, which means that the battery has a deep charge and discharge. Fig. 9(e)-(h) shows the results of the rainflow based battery degradation. According to the results of quantitative analysis, the lifetime loss of battery under GT, ECMS, MPC and RBS are 0.11%, 0.09%, 0.08%, 0.20%, respectively. For RBS, due to priority use of battery, the battery lifetime reduces the most in the four methods. In terms of GT, the PMS enables the battery to compensate for high demand load to protect fuel cell lifetime, thus, the battery degradation reduce more than ECMS and MPC. However, considering that the cost difference between fuel cell and battery, reducing the fuel cell degradation is a significant method to improve the system economy, which inevitable increase in battery degradation. Thus, from a global perspective, the game theory is a conservative and effective method to improve the performance of HBHS.

3.1.3. Hydrogen safety

In order to simplify the complicated changes in temperature, it is assumed that the temperature in the hydrogen storage tank is 313 K before each hydrogen filling. To evaluate the hydrogen safety during hydrogen filling, the temperature changes in the hydrogen tank during the hydrogen filling process with different methods are shown in Fig. 10. It can be seen that electrolyzer opening times and working hours are minimal resulting in that the maximum temperature of the gas in the hydrogen storage tank is the smallest under the RBS, which is due to the rule of prioritizing battery usage. Except for RBS, the temperature rise with GT is always minimal at the end of each hydrogen filling process. The maximum temperature with GT reaches 335.4 K, while the maximum temperature with ECMS is 338.8 K. Compared with ECMS and MPC, the maximum temperature of GT is reduced by 3.4 K and 2.9 K. It is evident that the electrolyzer with the proposed strategy can consider the safety of the hydrogen storage system while considering the hydrogen production efficiency, which improves the security of the hydrogen storage system.

3.2. Experiment and discussions

In order to verify the real-time and validity performance of the proposed method, a scaled-down smart building system experiment platform is set up. The structure of the experiment platform and control method is shown in Fig. 11, which is made up by two parts that the real-time power management in the top layer and real-time power control in the bottom layer. In the upper layer, the proposed power management strategy is implemented by the PC (i5-7300HQ, GTX 1050Ti), and the

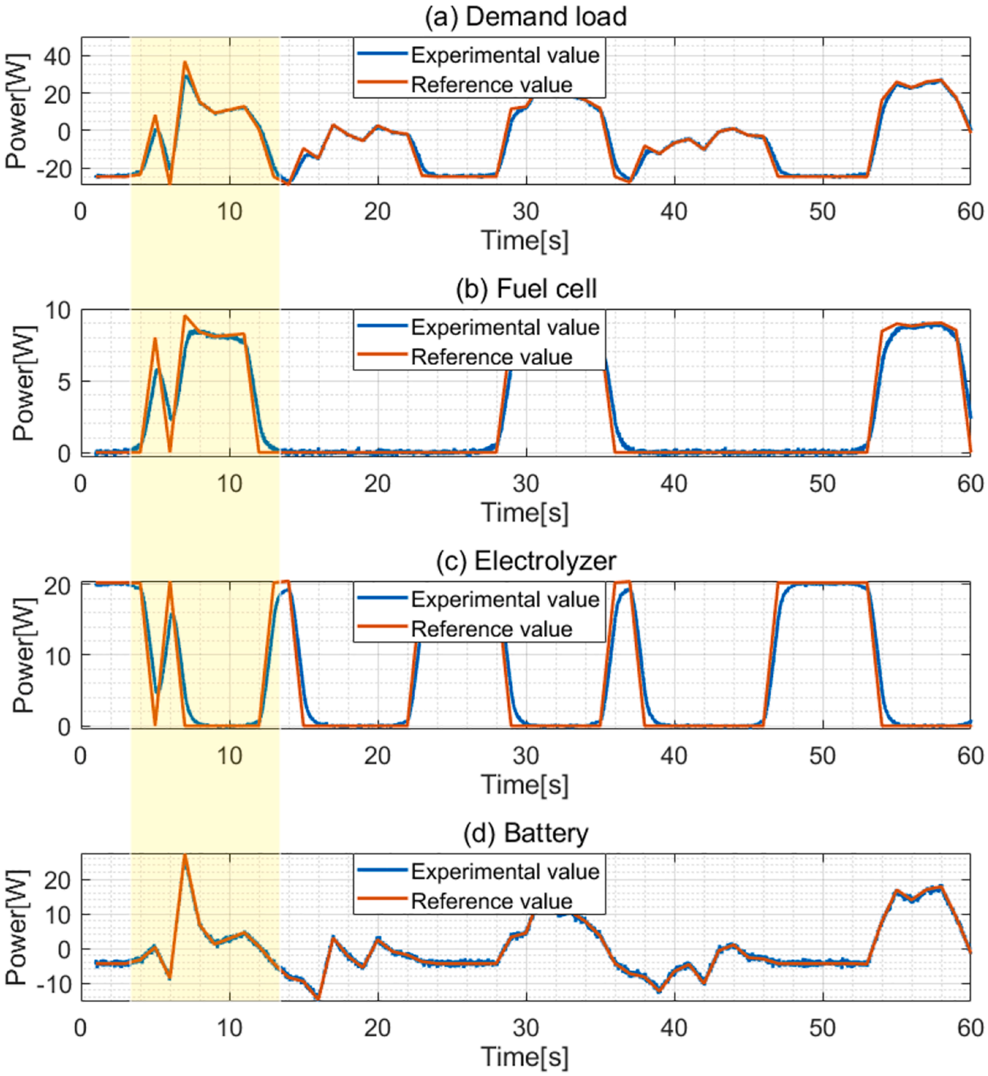


Fig. 12. Experiment results.

both the programmable load module and programmable source module take actions following the commends generated by the power management. The programmable source module is used to simulate photovoltaic power generation and the programmable load module is used to simulate building loads. In the lower layer, three batteries together with three DC/DC converters (synchronous rectifier buck circuit) and controllers (stm32F401RE) are used to simulated the fuel cell system, electrolyzer system, and battery system. In order to simulate the dynamic response characteristics of the fuel cell and the electrolyzer, the time constant modules are introduced, that 0.4 s and 0.7 s for the fuel cell and the electrolyzer respectively. The current closed-loop control is used to realize the power following. It is obvious that, the upper layer generates the power surplus and deficiency for the three energy storage devices, and DC/DC converter systems in the lower layer control the charge and discharge of these energy storage devices. In lower layer that the current control of the three energy storage devices is implemented in the real time, so that to verify the real-time capability of the proposed power management method in the upper layer. Experiment results are illustrated by the Fig. 12. It is very obvious that the fuel cell, electrolyzer and battery can follow the reference value in real time, which verifies the feasibility and real-time of the proposed power management strategy that the all the power control commands can be implemented in real-time. As the time constant modules are added in the power control layer as shown in Fig. 11, the fuel cell and electrolyzer cannot fully follow the reference value during the rapid load change condition (highlighted in yellow in Fig. 12), which exactly describe the relatively slow response speed of fuel cell and electrolyzer. However, during this period the battery comes into actions immediate responding to the power surplus and deficiency.

4. Conclusion

Towards the net-zero emission building system, a hydrogen and battery hybrid system including the fuel cell, electrolyzer and battery is designed and investigated in this paper. To address the challenge that difficult to deal with the different characteristics of difference energy sectors within the building system, a synergy power management approach is developed based on the max–min game theory. Under the proposed power management strategy, the different characteristics of the energy players are modeled by creating the competing relationship against the multi-objectives. The power management system considers fuel cell deterioration as a constraint to sustaining the fuel cell's high-efficiency working zone. In addition, pressure constraints are added to improve hydrogen safety by lowering the temperature of the hydrogen storage tank. Simulation results show that the proposed method outperforms other methods in suppressing fuel cell degradation, improving fuel cell efficiency as well as improving the hydrogen tank safety. The lifetime of the fuel cell with the proposed method is the optimal result which is extended by 5 years, 5.38 years and 2.3 years on average compared with ECMS, MPC and rule-based method. Meanwhile, the overall fluctuation of fuel cell output power is reduced by 16.60% and 10.57% compared with ECMS and MPC. Moreover, the maximum tank temperature reflecting the hydrogen safety of the hydrogen tank is reduced by 3.4 K and 2.9 K compared with ECMS and MPC. Besides, the proposed algorithm can significantly keep fuel cell and electrolyzer working in the high-efficiency range for 80% of the working time. Finally, the real-time of the proposed power management is verified by a scaled-down smart building system experiment platform.

CRediT authorship contribution statement

Jianwei Li: Conceptualization, Methodology, Software, Data curation. **Weitao Zou:** Writing - original draft, Formal analysis, Data curation. **Qingqing Yang:** Writing - original draft, Visualization, Investigation. **Huanhuan Bao:** Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This work is supported by National Key Research and Development Program of China with No.2021YFB2501504, and National Natural Science Foundation of China with No.52172354.

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