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Experimental Validation of Hydrogen Fuel-Cell and Battery-Based Hybrid Drive without DC-DC for Light Scooter under Two Typical Driving Cycles

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Abstract: Faced with key obstacles, such as the short driving range, long charging time, and limited volume allowance of battery-powered electric light scooters in Asian cities, the aim of this study is to present a passive fuel cell/battery hybrid system without DC-DC to ensure a compact volume and low cost. A novel topology structure of the passive fuel cell/battery power system for the electric light scooter is proposed, and the passive power system runs only on hydrogen. The power performance and efficiency of the passive power system are evaluated by a self-developed test bench before installation into the scooters. The results of this study reveal that the characteristics of stable power output, quick response, and the average efficiency are as high as 88% during the Shanghainese urban driving cycle and 89.5% during the Chinese standard driving cycle. The results present the possibility that this passive fuel cell/battery hybrid powertrain system without DC-DC is practical for commercial scooters.

Keywords: electric light scooter; proton exchange membrane fuel cell; passive fuel cell/battery hybrid system; urban driving cycles

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1. Introduction

Nowadays, citizens are faced with challenges of air quality and energy consumption in transportation [1]. Electric scooters are popular in both cities and urban areas all over the world, particularly in Asia [2–4], and they are usually powered by batteries. However, short driving ranges and long recharging times are inevitable challenges for battery-based electric scooters. The proton exchange membrane (PEM) fuel cell is a promising alternative energy resource, owing to its high efficiency, low operating temperature, quick start-up, zero-emission, etc. [5–7]. Thanks to the wide development of e-scooters, the PEM fuel cell can be installed in hydrogen-powered scooters and combined with batteries to extend their advantages in long ranges and quick refuels [8–10]. The fuel cell/battery hybrid powertrain system can meet the common power demand for e-scooters and a higher pulse power requirement than each energy resource alone [11–14]. The battery can provide traction assistance during acceleration to compensate for the fuel cell's slow ramp and assist the transient high output power so that a smaller fuel cell can be utilized [15].

In the past two decades, impressive developments have been achieved in the e-transportation application of the fuel cell/battery hybrid powertrain system [16–20]. Many researchers apply DC-DC converters to stabilize the fuel cell's output power and maintain the high efficiency of the powertrain system. Some studies have found that the main factors leading to the damage of the PEM fuel cell are caused by frequent load change, low power operation, and cold start-up [21,22], so stable output power is important during the operation of the fuel cell/battery hybrid system. However, the DC-DC converters which adjust and stabilize the voltages would also take up a certain installation volume and bring about an extra cost for the compact and low-cost scooters.

The passive hybrid powertrain system, in which the fuel cell stack is directly connected to the battery without DC-DC converters, offers great interest for the light e-scooter, owing to its compact installation volume, low mass, allowable cost, and simple powertrain system design. Although numerous theoretical studies and numerical simulations are favorable for understanding its basic principles [23–25], there are few studies that evaluate the efficiency and power characteristics during the dynamic operation; these factors play an important role in the fuel economy and long driving range and are key technologies in the commercialization of fuel cell scooters.

Jiang et al. [26] presented a conceptional compact fuel cell/battery hybrid energy system that was controlled by a current regulator to balance the power flow. The results showed that the fuel cell current, the battery charging current, and the battery voltage should be well controlled under complex dynamic conditions. Bernard et al. [27] put forward a kind of architecture of a passive fuel cell/battery hybrid system that was adjusted with the hydrogen/oxygen pressure and could satisfy the power demand. Eduardo et al. [28] proposed three types of configurations of a passive fuel cell/battery hybrid system with a switch to control the operation of the fuel cell stack and evaluated the power demand for a compact, unmanned ground vehicle. Wu et al. [29] also proposed a fuel cell/supercapacitor passive hybrid power system without DC-DC converters, which showed that efficiency rate gains of approximately 5% were achieved. Howroyd et al. [30] proposed a natural balancing strategy using diodes for protection in a passive hybrid system to prevent the high reverse current from the battery to the fuel cell stacks. The results revealed that it was possible to balance the voltage of the fuel cell with the battery without DC-DC converters. Taking these general characteristics into account, passive hybrid power systems based on fuel cells combined with batteries are a possible substitute option to power the electric scooter without the power losses of DC-DC, to increase efficiency and economic fuel consumption.

In the previous works, few studies have evaluated the power and efficiency of passive fuel cell/battery powertrain systems on the test bench for an electric scooter under complex dynamic loading conditions, and the wide range of the output voltage of fuel cells is also not favorable to its high performance [31]. Therefore, this study aims to propose a novel passive fuel cell/battery hybrid power system for the practical electric light scooter which will evaluate its power and efficiency characteristics by a self-developed test bench. Experiments with two typical dynamic driving cycles are induced to study the effectiveness of the hybrid system concentrated on electric scooter applications. The main objectives are organized as follows: (1) Propose a passive fuel cell/battery powertrain system and its control strategy; (2) Describe a self-developed test bench and typical dynamic driving cycles for evaluation; (3) Evaluate the dynamic characteristics of the passive powertrain system with two typical dynamic driving cycles.

2. Configuration of the Passive Fuel Cell/Battery Hybrid Systems for E-Scooters

Compared to the active fuel cell/battery hybrid topology, the main characteristics of the passive hybrid system are that the fuel cells and batteries are in parallel and directly connected to the main circuits without DC-DC converters and they drive the scooter together in consideration of high pulse power demand when the scooter starts up or accelerates [32]. The nominal voltage of the fuel cell stacks should be similar to the battery in order to avoid overcharge, and it should also be similar to the motor due to the lack of DC-DC converters.

In this study, one brushless dc (BLDC) motor (48 V & 500 W) is the load in this passive powertrain system, which is commonly used to drive the light electric scooter in Asian markets. Two fuel cell stacks are carefully selected and connected in a series to obtain the rated voltage of 48 V and power of 500 W for driving a BLDC motor with the same voltage and power. The fuel cell stacks are self-humidified [33,34], and the passive hybrid power system does not need the humidifier for the compact allowance installation volume. The polarization and power curve are shown in Figure 1, wherein the voltage of the fuel cell slightly decreases and the power curve quickly increases with the currents. The fuel cell stacks can provide stable output voltage and enough energy to power the battery and the motor during normal operating conditions.

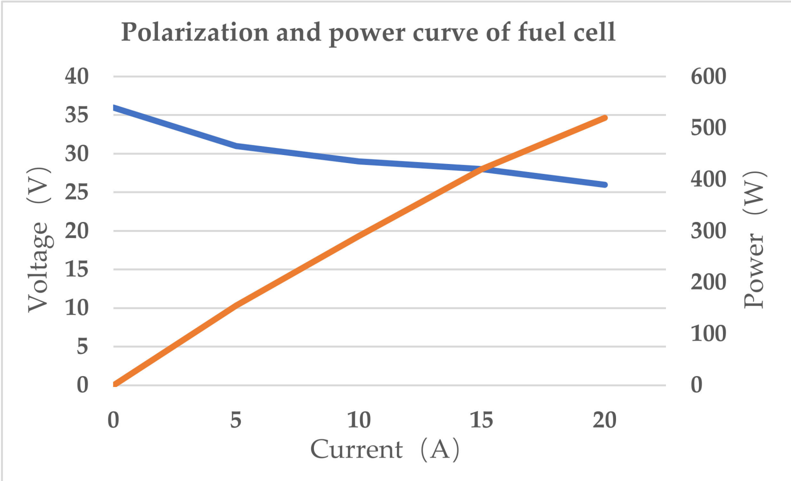


Figure 1. Polarization and power curve of each fuel cell stack.

In addition to the fuel cells, a Lithium-ion battery (48 V & 12 Ah) is installed as an energy baffle to provide the pulse power for the dynamic power requirement, which determines a fixed power flow from the fuel cell stacks to recharge the batteries and drive the motors. This battery contains a battery management system and, if necessary, disconnects the battery from the electric main circuit. The voltage of the battery is measured with a voltage sensor.

The schematic architecture of the complete passive fuel cell/battery hybrid power system for an electric scooter, with the hydrogen-flow, air-flow, main electric circuit, sensors, and control signals, is shown in Figure 2.

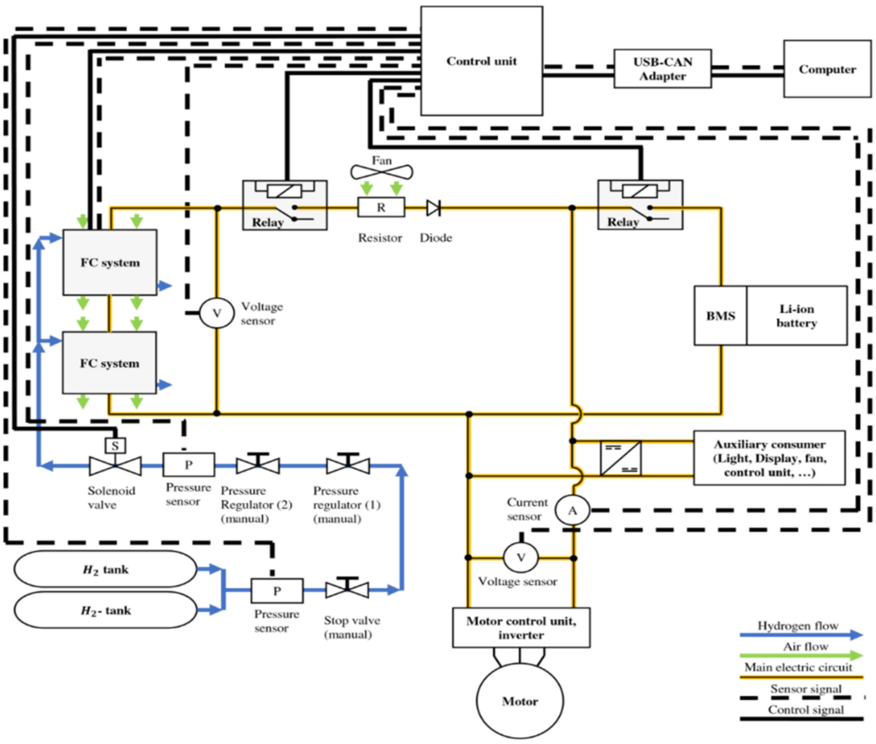


Figure 2. Architecture of the passive fuel cell/battery hybrid powertrain system for electric scooter.

As shown in Figure 2, compared to battery-based scooters, different designs are presented in this passive power system.

Firstly, the currents in the passive fuel cell/battery hybrid system naturally regulate themselves according to the resistors of the fuel cell stack and the battery. To restrict the current flow from the fuel cells to the batteries in case of battery charging, a 3 Ω power resistor is proposed to profit some power of the fuel cell to reduce the charging current of the fuel cell to the battery (I_{batt}) when the low load occurs during the electric scooter's dynamic operating. Meanwhile, the power resistor is cooled by a fan (12 V, 0.18 A). This can regulate the current of the fuel cell stack (I_{stack}) and protect the battery at the expense of a small amount of power (about 30 W), which will be evaluated later.

Secondly, the reverse current protection for the fuel cell is essential in the passive hybrid system, and a diode is connected in a series with the fuel cell stack to prevent the power from batteries recharging the fuel cells. It will block the charging current if the output voltage of batteries (U_{batt}) is higher than the voltage of fuel cell stacks (U_{stack}).

In addition, two relays as switches are unable to connect or disconnect the fuel cell from the main circuit, which are driven by the electronic control unit (ECU). As long as the switches are closed, the fuel cell and the battery will operate simultaneously to drive the BLDC motor. The motor is controlled by a motor control unit, which is connected parallel to the fuel cell and the battery. ECU is introduced to control the power flow of the passive powertrain system.

In order to better understand the passive fuel cell/battery hybrid power system for the e-scooter, some specifications for the major components are shown in Table 1.

Table 1. Specifications for the major components in the passive hybrid system for scooters.

Main Components	Description	Value	Units
Fuel cell stack	Rated power	500 (250 × 2)	W
	Rated voltage	48 (24 × 2)	V
	Cooling method	Air-cooling	
Lithium-ion battery	Rated voltage	48	V
	Capacity	12	Ah
BLDC motor	Nominal power	500	W
	Max. Power	1200	W
	Driving voltage	48	V
Compressed hydrogen tank	Nominal volume	6	L
	Max. pressure	35	MPa
Power resistor	Resistor	3	Ω

Here, a finite state machine (FSM) energy management strategy [30] is introduced to control the power flow between the fuel cells and battery of the hybrid power system. The relays between different states are controlled according to the state of charge (SOC) of the battery. The charging/discharging current of the battery is monitored in real time by sensors, and the SOC of the battery is calculated using the current integration method [35,36].

The main operating control strategies of the fuel cell/battery hybrid scooter are proposed as follows:

(1) If the SOC of the Li-ion battery is higher than a certain level (in this study, the value is set to 90% in order to maintain sufficient power for a relatively high pulse power requirement of the scooter on-road and for the purpose of hydrogen power, which is controlled by FSM strategy), the relay and the solenoid valve of hydrogen inlet will be switched off and the BLDC motor is directly powered by the Li-ion battery in this condition;

(2) If the SOC of the battery drops below 90%, both the solenoid valve of hydrogen and the relay will switch on, i.e., if the scooters are under high load conditions, such as climbing or accelerating, the fuel cell can enhance the capability of output power together with the battery to power the BLDC. When the power demand from the motor is relatively low, the fuel cell will drive the motor and simultaneously charge the battery to increase its SOC to 90%;
(3) If the hydrogen in the tanks is exhausted or improper working conditions occur (i.e., overheating of fuel cell stacks/hydrogen leakage/sudden voltage drops of stacks, etc.), the solenoid valve and the relays will be switched off and stopped until normal working conditions return. Meanwhile, the BLDC motor is powered only by the battery.

The overall efficiency and the specific power of such a passive hybrid system should be evaluated and validated to result in the constant rated current, power resistor, and reverse current protection device.

3. Test Bench and Dynamic Urban Driving Cycles for Experimental Validation

3.1. Test Bench

To validate the effectiveness of the passive fuel cell/battery hybrid power system and analyze its performance (efficiency, power, working current, etc.) under different dynamic driving cycles, a self-developed passive fuel cell/battery powertrain system is set up on a test bench, and a series of experimentations are conducted.

The BLDC motor is replaced by a Kikusui DC electronic load, its maximum allowable power of the electronic load is 1500 W, which can work with three modes as constant current, constant voltage, and constant power. During these tests, power spectra are induced by this DC electronic load to simulate the power demand from the motor and response data from the power system, e.g., U_{stack}, I_{stack}, U_{batt}, I_{batt}, are measured by the corresponding sensors and collected by ECU. The main components of the test bench are shown in Figure 3.

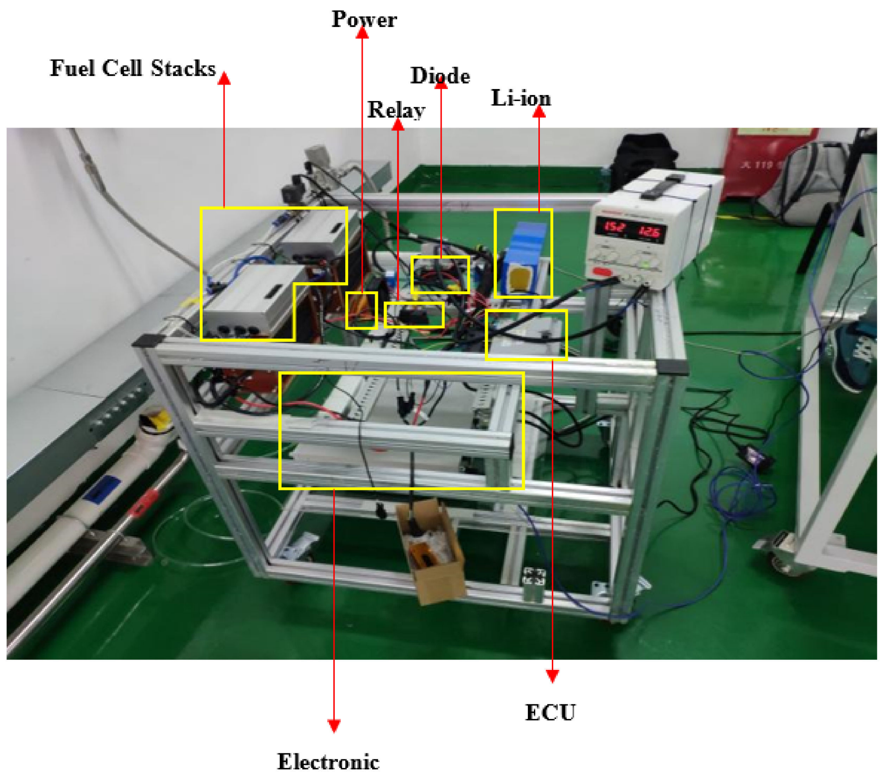
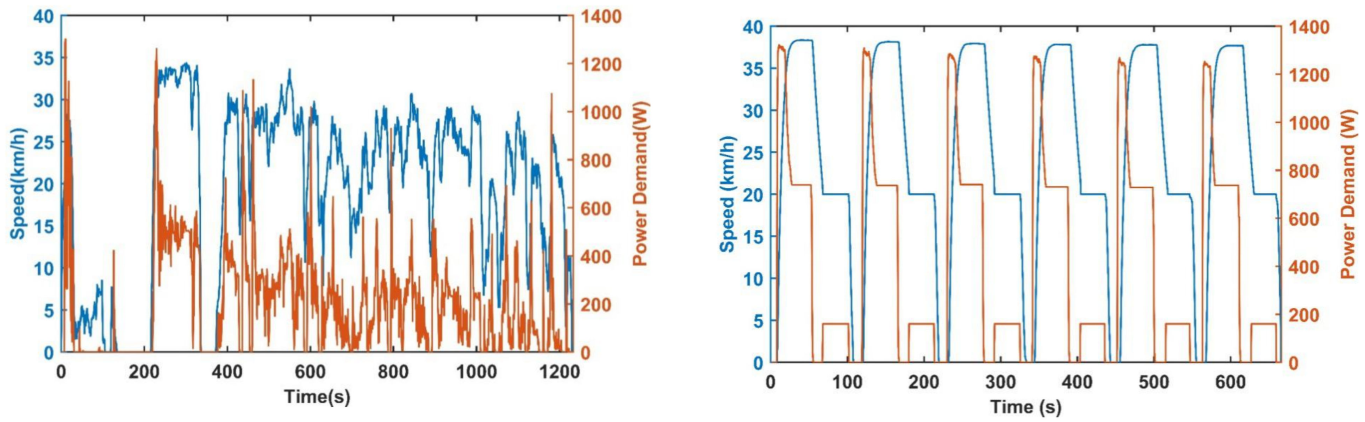


Figure 3. The passive fuel cell/battery hybrid power system on the test bench.

3.2. Dynamic Urban Driving Cycles

The driving cycles are important to validate the performance of the hybrid power system for an e-scooter. Two typical test cycles are introduced as the Shanghainese urban driving cycle and the Chinese standard driving cycle for this passive fuel cell scooter.

The driving speed of the Shanghainese urban driving cycle is tested with a pure e-scooter running on ordinary roads in Shanghai city, and the selected recorded duration is 1233 s. During this typical driving cycle, quick start-up, acceleration, deceleration, waiting for traffic lights, and driving at a constant speed are all included. The driving speed and power demand of the BLDC motor are shown in Figure 4a. The average and maximum speeds of this cycle are 18.2 km h^{-1} and 34 km h^{-1}, respectively. The maximum power of this driving cycle is about 1300 W. Since this driving cycle is recorded by a scooter running on roads under a realistic and complicated traffic condition, the experimental validation results under this cycle can be proof of the adaptive capabilities of the passive fuel cell/battery hybrid power system.



(a) (b)

Figure 4. Driving speed and power demand of two typical driving cycles: (**a**) Driving speed and power demand of the Shanghainese urban driving cycle; (**b**) Driving speed and power demand of the Chinese standard test cycle.

The other driving cycle is the Chinese standard driving cycle for e-scooter. The driving speed and power demand are shown in Figure 4b. This cycle comes from the Chinese standard GB/T 24157-2009, which is always used to evaluate the performance and the driving range for e-scooters. The average and maximum speeds of the Chinese standard driving cycle are 24.1 km h^{-1} and 38.3 km h^{-1}. Since the maximum power of this driving cycle is 1300 W, compared to the Shanghainese urban driving cycle, the Chinese standard driving cycle has a higher average speed and maximum speed.

These two typical dynamic cycles are suitable for the test bench for the passive fuel cell/battery hybrid powertrain system analysis of the light scooters. The individual driving modes, such as acceleration, braking, and constant speed, can be clearly distinguished from each other.

4. Results and Discussion

Since the stable output power of the fuel cell is essential to its long durability, the output power under these two driving cycles will be evaluated and validated for the effectiveness of the passive hybrid system of the e-scooter. Meanwhile, the efficiency of the hybrid power system will also be analyzed for the performance and economy. Based on the test bench and these two driving cycles, the power of the fuel cell/battery hybrid system and the electric efficiency of the fuel cell stacks is evaluated, and the results are shown in Figures 5 and 6.

4.1. Power Evaluation

As shown in Figure 5a, the power requirement of the motor varies significantly and rapidly under the Shanghainese urban driving cycle, which resulted in frequent acceleration and braking. The output power of the fuel cell is almost constant due to the output power of the battery as a buffer. The tested average output power of the fuel cell is about 304 W, and the maximum variation amplitude of the fuel cell is about 52 W, which is relatively small compared to its average output power.

The output power of the fuel cell is stable for this passive hybrid power system, which is better for its long lifetime. The battery can provide extra energy if the scooter has a high-power requirement, such as accelerating or climbing conditions. The battery can be recharged by the fuel cell, thanks to the parallel connection of this hybrid system when the power demand of the motor is lower than the output power of the fuel cell stacks.

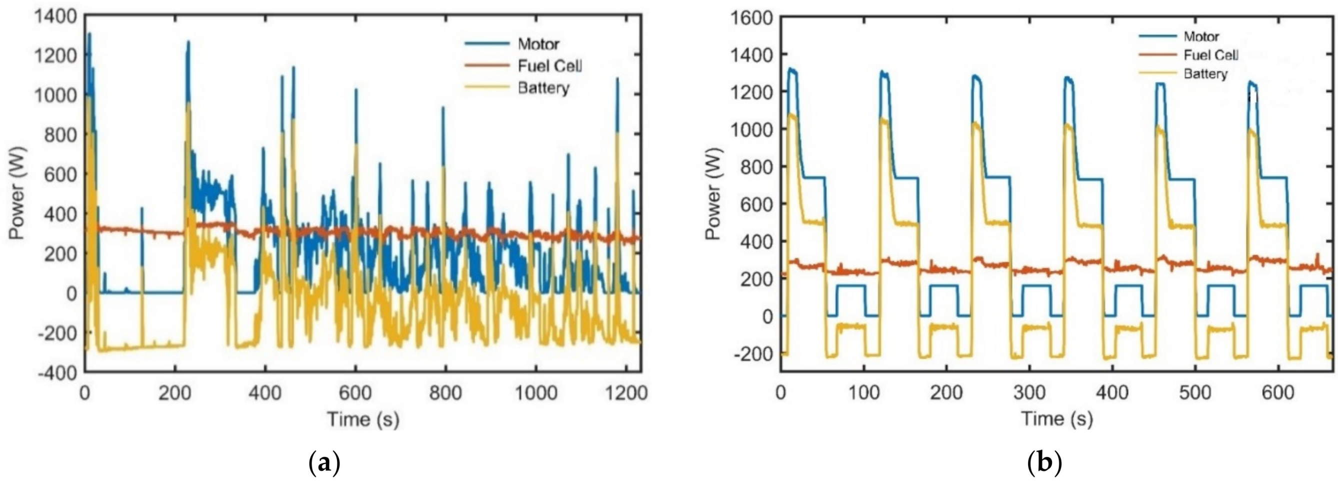


Figure 5. Power distribution of the passive hybrid power system for the e-scooter: (**a**) Power requirement under the Shanghainese urban driving cycle; (**b**) Power requirement under the Chinese standard driving cycle.

Figure 5b shows the power distribution characteristics under the Chinese standard driving cycle, which is similar to the power distribution under the Shanghainese urban driving cycle. The passive hybrid power system is effective to fulfill the power requirement of the motor while maintaining the stable output power of fuel cells. However, during the variance of the power of the BLDC motor, the current of the bus will vary, which may challenge the efficiency of the hybrid power system.

4.2. Efficiency Evaluation

Since a power resistor is set between the fuel cell stacks and the main circuit to stabilize the output power of the fuel cell stacks and restrict the charging current from the fuel cell stacks to the battery, some electrical energy generated by the fuel cell stacks will be transformed into the form of heat. The working efficiency should be evaluated to represent the performance of the passive hybrid power system. Considering the power loss of the resistor, the electric efficiency of a fuel cell stack can be defined as:

$$\mathrm{eff}_{\mathrm{elec}} = 1 - \frac{\mathrm{P}_{\mathrm{loss}}}{\mathrm{P}_{\mathrm{stack}}} \quad (1)$$

where $\mathrm{P}_{\mathrm{loss}}$ represents the power loss on the power resistor, which can be obtained based on the resistor and the working current, and $\mathrm{P}_{\mathrm{stack}}$ represents the output power of the fuel cell stacks, which can be obtained by its working current and voltage. $\mathrm{eff}_{\mathrm{elec}}$ indicates the electric efficiency of energy from the fuel cell stacks, which is used to drive the motor and charge the battery.

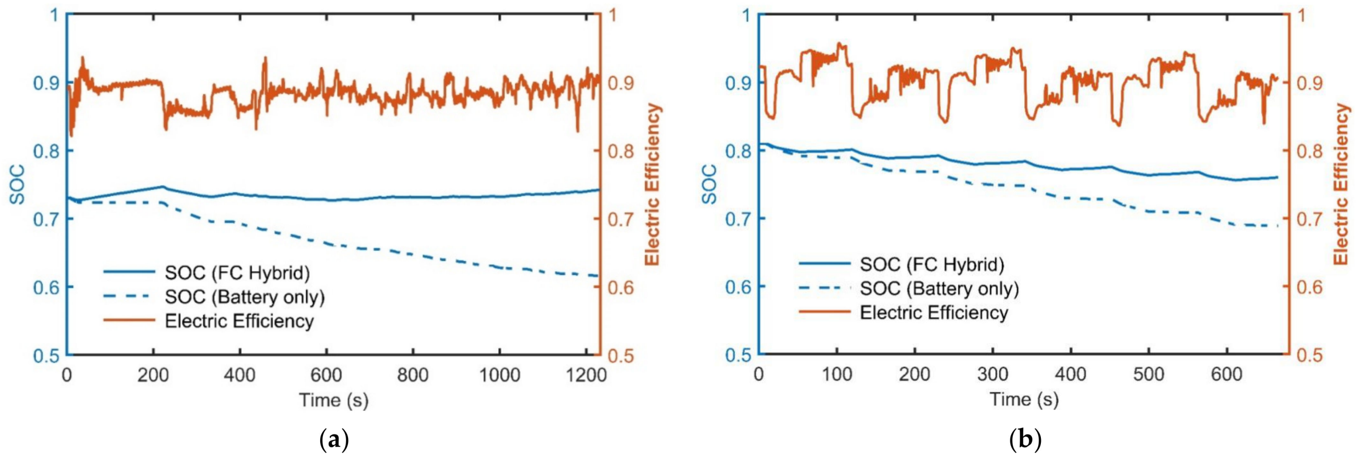


Figure 6. Electric efficiency of the fuel cell stacks under driving cycles: (**a**) Shanghainese urban driving cycle; (**b**) Chinese standard driving cycle.

Firstly, the tested electric efficiency of the fuel cell stacks eff_{elec} under two typical driving cycles is shown in Figure 6, which is varied according to the variable current of the bus and the power demand of the motor. However, the high output power demand of the motor results in the falling of the battery's SOC, and the output current of the fuel cell will increase and result in more energy loss for the power resistor.

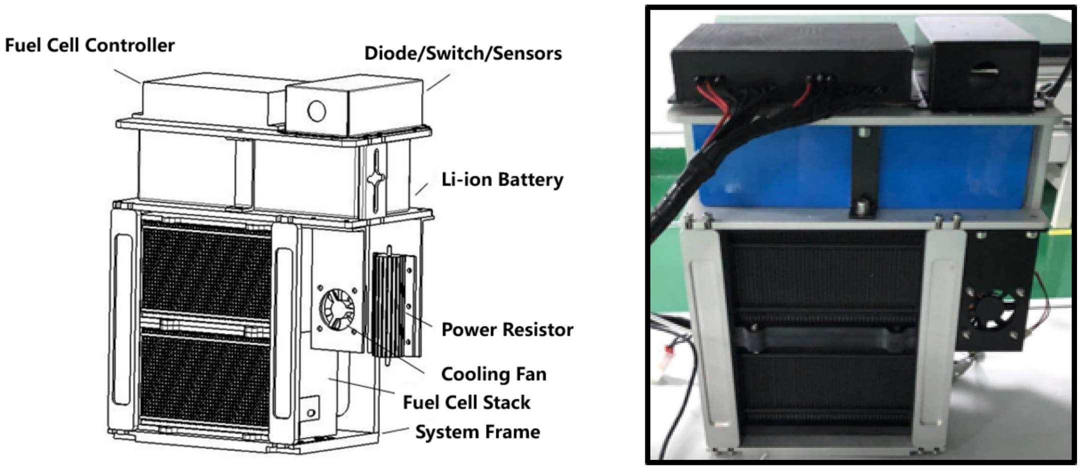
However, due to the small power resistor applied in this study, the average efficiency is still relatively high, as obtained by the electric efficiency lines as shown in Figure 6 (88% in the Shanghainese urban driving cycle and 89.5% in the Chinese standard driving cycle), similar to the active hybrid power system with a DC-DC converter [37–39]. It can be revealed that the passive fuel cell/battery hybrid power system is relatively effective under these two typical driving cycles for a commercial light scooter on the road.

Secondly, as shown in Figure 6, the solid curve represents the SOC of the battery under two driving cycles, and the dashed curve represents the SOC of the battery in the case of a pure battery power system (e.g., the hydrogen exhaust). The results of the different SOCs indicate that the passive hybrid power system decreases the energy consumption of the Li-ion battery, and the SOCs under the two driving cycles maintain a relatively high level, especially in the Shanghainese urban driving cycle. However, this also suggests that the fuel cell is likely undersized for the application.

In this passive hybrid power system, it is not necessary to recharge the battery but only to refuel the hydrogen tank because the fuel cell charges the battery in a large part of the working time. The electric energy provided by this passive powertrain system of the scooter is transformed by the hydrogen, so a scooter equipped with such a power system can be regarded as a scooter running on hydrogen.

Based on this concept, a practical design of a passive fuel cell/Li-ion battery hybrid system for an e-scooter is proposed, as shown in Figure 7. Since all components in this design are cleverly located, the total volume of the system is only $273 \times 150 \times 373.6$ mm^3, so that it can be easily installed in a light commercial e-scooter.

After the practical module was produced and assembled, it was installed into an e-scooter, as shown in Figure 8. The whole compact power module is installed under the seat, and the hydrogen supply system is under the footrest. The results of the structural modification prove that this design of power module can well fit a normal size of the light scooter. However, it is highlighted that there are some disadvantages of this system, such as the low velocity, thermal balance problem, etc. Further tests will be launched in future research, including road tests to validate the economy and degradation of the fuel cell stack.



(**a**) (**b**)

Figure 7. Practical design of passive fuel cell/Li-ion battery hybrid system for an e-scooter: (**a**) Structural design; (**b**) Practical module.

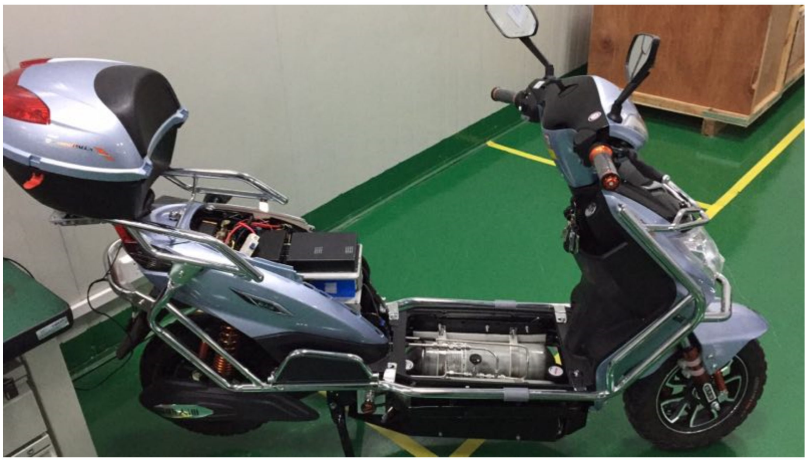


Figure 8. The e-scooter equipped with the passive fuel cell/Li-ion battery hybrid system.

5. Conclusions

In this study, a passive PEM fuel cell/Li-battery hybrid power system for e-scooters is proposed, and an experimental evaluation is conducted to characterize the stable output power and the electric efficiency of the fuel cell in the passive hybrid power system under two typical driving cycles.

In detail, at first, a novel configuration of the passive fuel cell/battery hybrid power system for an e-scooter with a power resistor and a diode is proposed for the low cost, and the power output feature of fuel cell stacks and battery are well matched for the same voltage. Simultaneously, the test bench is self-developed and set up to experimentally evaluate the power demand and electric efficiency under two driving cycles with realistic and complicated traffic conditions.

Then, the results showed that the output power of fuel cell stacks is stable, which contributes a good performance and long lifetime to the light scooters, and it can also maintain a good consistency of the stable output power of fuel cells under two typical driving cycles of this passive hybrid power system for the electric scooter.

Finally, the electric efficiency analysis of fuel cell stacks in the passive hybrid power system is evaluated and validated. The average efficiency of the passive hybrid power system is relatively high (88% in the Shanghainese urban driving cycle and 89.5% in the

Chinese standard driving cycle). Based on this evaluation, the passive fuel cell/battery hybrid system without DC-DC converters is practical for commercial scooters.

The efficiency of the passive hybrid system is closely related to the fuel cell operating point, which can be carefully controlled by means of an advanced control system. Therefore, the energy management of the scooter will be optimized at different operating parameters and power demands by the scooter, depending on the type of driving cycle.

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