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Economic Operation Strategy of Multitype Emergency Power Supply Taking into Account Carbon Cost

Wang Tingyan*[1], Huang Qingdan*, Zhao Chongzhi*, Huang Huihong*, and Song Haoyong*

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ABSTRACT

Emergency power is the core power equipment to guarantee power in communication, emergency repair and medical. However, such factors as pollution and energy storage capacity restrict the development of emergency power toward a clean and low-carbon new power system. Aiming at the emergency power system of diesel generator, $LiFePO_4$ battery and fuel cell that using hydrogen and methanol as fuel, taking the levelized cost of energy (LCOE) of the system as the index. The economic operation strategy of the emergency power supply was put forward, and the sensitivity analysis of key parameters and the feasibility analysis were studied. The results show that short and small-scale (0-4h, 1kW) power backup using $LiFePO_4$ battery is better at present. Medium and long (5-80h) power backup using diesel generator and long (≥80h) power backup using solid oxide fuel cell (SOFC) methanol are more economical. In future, $LiFePO_4$ battery will become the optimal economic solution for short-term, small-scale and high-frequency power backup. SOFC hydrogen, proton-exchange membrane fuel cell (PEMFC) hydrogen and SOFC methanol will become the optimal low-carbon economic solution for long-term continuous power backup, and it is feasible to use fuel cell as emergency power.

1. INTRODUCTION

Stable power supply is the basis for maintaining the social operation and development. However, natural disasters and grid accidents may cause failure of the power system inevitably [1]. Emergency power is the core power equipment to guarantee power in communication, emergency repair and medical purpose [2]. In recent years, China has successively issued various policies to actively promote the construction of new power systems and the industry development and facilitate the realization of the energy transformation goal of "having CO_2 emissions peak before 2030 and achieving carbon neutrality before 2060". The first task is to "build a clean, low-carbon, safe and efficient energy system, and build a new power system with new energy as the main body". The cleanliness, low-carbon, safety, and high efficiency are the characteristics of the new power system. How to evaluate the low-carbon economy of emergency power supply under the premise of ensuring emergency power supply is an important research direction of the power system at this stage. It will shorten the power outage time and reduce the power outage loss [3].

Currently, emergency power is mainly supplied by diesel generators and energy storage batteries. However, such factors as pollution and energy storage capacity restrict the development of emergency power toward a clean and low-carbon new power system. Diesel generators generate electricity by burning diesel. The combustion will emit CO_2, SO_2 and other gases, which have certain pollution. It is of high quality and are not easy to move，which are suitable for emergency power supply in fixed scenarios [4]. Lead-acid batteries and $LiFePO_4$ batteries are two common energy storage batteries. They are charged and stored in the non-use phase and used in an emergency when the power system fails. However, the energy storage battery is limited by its capacity and cannot achieve long-term continuous power supply, and early production pollution. The recycling costs are higher.

Fuel cells, as a new type of power equipment featuring high power generation efficiency, a wide range of fuel sources, good waste heat quality, and other advantages [5], have drawn great attention in the field of emergency power [6]-[7]. Moreover, only water and power are produced in the service of fuel cells, so additional revenues can be gained via carbon trading and the cost-effectiveness can be improved. Fuel cells are now under development, with high costs of equipment production and fuel procurement. Both the industry and academia are concerned about the economic feasibility of widely using fuel cells as the emergency power.

In this paper, with levelized cost of energy (LCOE) of the emergency power taken as the index, an economic evaluation model for emergency power is established based on the costs of fuel, depreciation, repair and accessories. In this model, the cost-effectiveness of the new low-carbon power system as the emergency power is evaluated. The major factors affecting the cost-

*Guangzhou Power Supply Bureau, Guangdong Power Grid Co., Ltd., Guangzhou, 510620, China.

[1] Corresponding author;
E-mail: 2897612589@qq.com

effectiveness are analyzed, and the sensitivity of these factors are expounded. Considering the carbon trading mechanism, predict the life-cycle cost of emergency power supply in 2030. Finally, this model is applied to the emergency power system of the communication base stations in service to verify the feasibility of using fuel cells as the emergency power.

2. EMERGENCY POWER

2.1 Technical Route

Diesel generators, energy storage batteries, and fuel cells are three types of emergency power sources that have been used or are in the demonstration stage. They have a wide range of application scenarios that are often used in communication, hiking, lighting, power, medical, rescue and so on. As shown in Figure 1, there are various energy sources for emergency power supply. Diesel generators can obtain energy by burning diesel to drive power generation. Energy storage batteries such as lead-acid batteries and $LiFePO_4$ batteries can be charged by mains electricity when there is no power outage. Or use diesel generators, fuel cells and other power generation equipment to charge. Fuel cells obtain electricity through the electrochemical reaction of hydrogen. Hydrogen can be obtained by reforming raw materials such as natural gas and methanol.

According to Table 1, diesel generators have low efficiency and high noise level and emit polluted gases. The lead-acid battery and $LiFePO_4$ battery have high efficiency, but short service life and cannot provide long-term continuous power supply due to $LiFePO_4$ battery capacity and load. Moreover, the operating temperature of the lead-acid battery must be controlled properly, increasing the temperature control cost. The solid oxide fuel cell (SOFC) and proton-exchange membrane fuel cell (PEMFC), with a generation efficiency of 40-60% and a wide range of operating temperature, can provide long-term power supply through fuel supply in service period, without any emission of pollutants. Nevertheless, these fuel cells are not fully marketized and their service costs remain high.

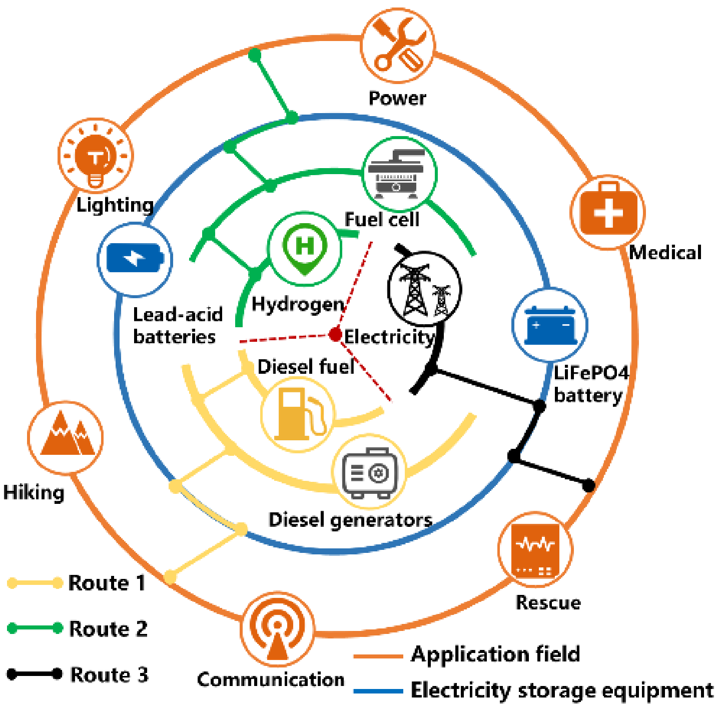

Fig. 1 Technical route of emergency power

The performance parameters of different emergency power sources are shown in Table 1. Diesel generators have low efficiency, only 20-30%. However, it has a long service life and can achieve long-term stable power supply through online fuel supply. Diesel generators need to compress and burn diesel for power generation, which is noisy and emits nitrogen oxides, carbon oxides and other polluting gases. Lead-acid batteries and $LiFePO_4$ batteries have the highest efficiency, but the battery life is short and cannot achieve long-term continuous power supply. The power supply time is limited by the battery capacity and load size, and the applicable power range is relatively fixed. If the applicable power needs to be changed, the total capacity can be increased by increasing the number of battery packs. At the same time, the operating temperature range is narrow and cannot be used in bad weather. In addition, lead-acid batteries have strict temperature control, which increases the cost of additional temperature control. The fuel cell has a power generation efficiency of 40-60%, a wide operating temperature range, and is less affected by the environment. Long-term power supply can be achieved through continuous and stable online fuel supply without pollutant emissions. Capacity can be expanded by adding battery modules. Completely market-oriented, the use cost is high.

Table 1. Emergency power supply classification and performance comparison.

Equipment	Diesel generator [8], [10]	Lead-acid battery [8], [10]	$LiFePO_4$ battery [8], [10]	SOFC [9]-[10]	PEMFC [9]-[10]
Efficiency (%)	20-30	> 80		50-60	40-50
Temperature (°C)	-5-45	0-3	0-40	600-1000	25-80
Service life (year)	10	4	8	10	10
Whether it can supply power continuously or not	Yes	No		Yes	
Pollution	NO_x, CO_x, NO_x and CO_x	High level of pollution from operation		None	
Power expansion	By replacing the generator set	By increasing module capacity		By increasing module capacity	
Disadvantages	Heavy equipment	Strict temperature control	High recycling cost	High manufacturing cost	High gas purity

2.2 Development

Diesel generators obtain energy from burning diesel to drive power generation, with a wide power range, which is 24 kW-1,200 kW for those developed by the major manufacturers in China, are the most widely used solution of emergency power. According to Global Data, diesel generators in the Asia-Pacific region accounted for 26.8% of the global market in 2017. It is predicted that from 2018 to 2022, the global market value of diesel generators will reach USD 115.1 billion, and China will seize 19.5% of the global diesel generator market by 2022.

In the fuel cells, electric energy is generated through the electrochemical reaction of hydrogen and oxygen. However, the amount of hydrogen used is small and its purity is high, resulting in high hydrogen purchase cost. And high pure hydrogen is a dangerous chemical and requires high storage safety. Comparatively, it can reduce the cost and realize the safe use of hydrogen by producing hydrogen with non-hydrogen materials like methanol or natural gas through reforming reaction on the site. Fuel cells developed by SFC Energy, SAFCells, Adaptive Energy and some other companies have been applied as off-grid power supply in fields such as military, remote monitoring and UAV, with a scale of 10,000 sets. The EFOY fuel cell series developed by SFC Energy can use hydrogen and methanol as fuel to generate electricity as a vehicle power supply or off-grid power supply, and can also be combined with a lithium battery as a hybrid power supply for charging portable devices, with a maximum output power of 2500 W. SAFCells uses methanol as fuel to develop emergency fuel cells with a maximum continuous power of 50 W and a usage time of 72 hours in the oil and gas field and military field. Adaptive Energy focuses on the development of 250-400 W fuel cells for remote monitoring, drones and other fields. In China, the use of fuel cells for power supply is still in the demonstration stage [6], and in the communication field, their operating hours are more than 40,000. At present, 3-5 kW hydrogen and methanol fuel cells are the most commonly used.

Energy storage batteries such as lead-acid batteries and $LiFePO_4$ batteries have the characteristics of easy portability and high-power density. The energy storage battery is the emergency power solution with the fastest market share at present. It is mainly used in communication security, power storage, transportation power, recycling, and industrial backup. Compared with the lead-acid battery, the $LiFePO_4$ battery has longer service life, wider range of operating temperature, and other advantages, and is more fit for use as a long-term energy storage medium. By the end of 2018, Chinese communication companies had used about 1.5 GWh of lithium iron phosphate batteries in about 120,000 base stations, replacing about 45,000 tons of lead-acid batteries. In 2019, about 5 GWh of lithium iron phosphate batteries were newly used in the backup power supply of China's communication base stations, and about 150,000 tons of lead-acid batteries were replaced. Lead-acid batteries are explicitly declared out of use in the new energy storage projects concerning base station and wind power in China in 2020. In the future, they will be gradually replaced by the $LiFePO_4$ batteries and thus will not be considered as the power supply solution in this paper.

3. EVALUATION MODEL

3.1 Levelized Cost of Energy (LCOE)

In this paper, an evaluation model is established by taking the LCOE as the index to analyze the cost-effectiveness of emergency power. LOCE includes two categories: initial input cost and operating cost. The initial input cost is mainly equipment cost, which is expressed as equipment depreciation cost and accessory cost according to the power backup duration and power range. Operating costs include fuel consumption cost and repair cost. The LCOE is expressed as:

$$C_{all} = C_{\mathrm{full}} + C_{\mathrm{dc}} + C_{\mathrm{re}} + C_{as} \quad (1)$$

Where, C_{all} means the LCOE; C_{fuel} the fuel consumption cost; C_{dc} the depreciation cost; C_{re} the repair cost; and C_{as} the accessory cost.

3.2 Fuel Consumption Cost

(1) Diesel generators
Diesel generators use diesel as fuel and use the diesel engine as the prime mover to drive the electric motor to generate electricity.

$$C_{fuel} = AM_{diesel} \tag{2}$$

Where, A means the diesel consumption; and M_{diesel} the diesel price.

(2) Fuel cells
Consider fuel cell emergency power systems with hydrogen and methanol as energy sources, respectively. Hydrogen and oxygen produce water and electricity through electrochemical reactions without harmful gas and carbon dioxide emissions. A fuel cell using methanol as a fuel needs to undergo a reforming hydrogen production reaction in advance to produce hydrogen, which is fed into the fuel cell to generate electricity.
Hydrogen consumption:

$$C_{fuel} = S_{fuel,H_2} \cdot \mathrm{M}_{fuel,H_2} \tag{3}$$

Where, $M_{fuel,\,H2}$ means the hydrogen price.

$$S_{fuel,H_2} = \frac{3.6}{\eta \cdot LHV} \tag{4}$$

Where, η means the power generation efficiency; and LHV the lower heating value of hydrogen.
Methanol consumption:

$$C_{fuel} = \frac{S_{fuel,H_2}}{1.26} \cdot M_{fuel,CH_4O} \tag{5}$$

Where, $M_{fuel,\,CH4O}$ means the methanol price.

(3) $LiFePO_4$ batteries
As a kind of energy storage battery, the lithium iron phosphate battery stores electric energy after charging and is directly connected to the load equipment when used. The survey found that most companies that use batteries take direct replacement after battery damage. So the maintenance cost and auxiliary material cost are not calculated. This paper considers the scheme of charging the lithium iron phosphate battery with mains power when there is no power failure. It is assumed that after a single discharge, it is fully charged and then used.

$$C_{fuel} = \frac{C_{BC}}{E_{all}} \tag{6}$$

Where, C_{BC} means the charging cost; and E_{all} the full-cycle discharge capacity.

$$C_{BC} = P_e \cdot \sum_{m=1}^{n} E_{cm} \tag{7}$$

Where, E_{cm} means the charging capacity of the mth cycle, where $0 < m \le n$; and P_e means the electricity price.

$$E_{cm} = \frac{\left[1-(m-1)\cdot a\right]\cdot V_{B,m} \cdot U_c \cdot N \cdot b}{1000c} \tag{8}$$

Where, U_C means the battery charging voltage; m means the number of cycle; and $V_{B,m}$ means the battery specification provided by the manufacturer.

$$E_{all} = \frac{t_{load} \cdot I_{load} \cdot U_{load} \cdot n}{1000} \tag{9}$$

Where, t_{load} means the continuous working duration per time; I_{load} the working current; U_{load} the working voltage; and n the total number of cycles.

3.3 Depreciation Cost

(1) Diesel generators and fuel cells

$$C_{\mathrm{dc}} = \frac{C_0}{\mathrm{t} \cdot P} \tag{10}$$

Where, C_0 means the equipment price; t the working hours; and P the backup power.

(2) $LiFePO_4$ batteries

$$C_{dc} = \frac{C_B}{E_{all}} \tag{11}$$

Where, C_B means the purchase cost.

$$C_B = P_{B,s} \cdot N \tag{12}$$

Where, $P_{B,s}$ the price of a single battery; and N the number of batteries required.

$$N = \frac{V_{B,need}}{V_{B,m}} \tag{13}$$

Where, $V_{B,need}$ means the backup power required.

3.4 Repair Cost

(1) Diesel generators

$$C_{\mathrm{re}} = \frac{C_{re1} + C_{re2} + C_{re3}}{t \cdot P} \tag{14}$$

Where, C_{rei} means the cost of repair for the ith time.

A diesel generator should be overhauled about every 30,000 h and discarded after three times of overhaul [9].

(2) Fuel cells

$$C_{re} = \frac{0.4C_0}{t} \tag{15}$$

The repair cost is estimated at 40% of the manufacturing cost of a SOFC / PEMFC.

3.5 Accessory Cost

$$C_{\mathrm{as}} = \sum_{1}^{i} \frac{C_i}{t_i \cdot P_i} \tag{16}$$

Where, C_i means the purchase price of the ith accessory, and Pi the backup power for the ith accessory.

4. ECONOMIC ANALYSIS

4.1 Boundary Description

The cost-effectiveness of emergency power is analyzed based on its application in basic scenarios like post-earthquake rescue and relief. In the earthquake rescue and disaster relief scenario, the main electrical equipment is shown in Table 2. Emergency electrical equipment is powered by battery and direct power-on. Equipment powered by battery needs to be recharged after the battery is discharged to a certain level. Therefore, considering the total power of each equipment and leaving a certain margin, the system target power is set 1 kW [6]. The analysis is carried out under the boundary conditions in Table 3, with the current equipment costs listed in Table 4.

Table 2. Emergency electrical equipment.

Application	Equipment	Source
Detection	Gas detector	Lithium battery, 2,000 mAh
	Water quality analyzer	Lithium battery, 2,600 mAh
Search	Infrared life detector	Lithium battery, 5,000 mAh
	Electromagnetic life detector	Lithium battery
Power lighting	High power LED	50 W
	Submersible pump	350 W
Rescue	Portable medical refrigerator	200 W
Communication	Intercom repeater	50 W

Table 3. Boundary conditions.

Boundary conditions	Boundary 1	Boundary 2	Boundary 3	Boundary 4
System	Backup power: 1 kW	Backup for 24 consecutive hours	Backup once a week	-
Diesel generator	Diesel: USD 0.9 /L	Service life: 10 years	-	-
$LiFePO_4$ battery	Mains supply: USD 0.085 /kWh	Service life: 8 years	Single pack of battery of 2.56kWh, 12 V 250 Ah, with a maximum of 1,500 cycles	Attenuation rate: 0.004 /time; depth of discharge: 0.8; charge/discharge efficiency: 0.9
Fuel cell	Methanol: USD 0.672 /kg	Service life: 10 years	Power generation efficiency: 55% for SOFC and 45% for PEMFC	4N hydrogen: USD 1.68 /Nm^3 cylinder; cylinder: USD 0.14 /day·cylinder

Table 4. Equipment cost.

Solution	Price (USD)	Specification	Source
Diesel generator	133	1300 W，220 V	Market survey
$LiFePO_4$ battery	487.2	12V200 Ah	Market survey
SOFC	4998	1000 W	Sun Kening[12]
PEMFC	1606.5	1000 W	Ballard[13]
SOFC reforming reactor	2.800	1 Nm^3/h	Market survey
PEMFC reforming reactor	9.250	1 Nm^3/h	Market survey

4.2 Analysis of Typical Scenarios

Figure 2 shows the LCOE of the emergency power supply under different power backup duration. With the increase of power backup duration, the life cycle of emergency power systems other than lithium iron phosphate batteries gradually decreases. After 24 hours of backup power, the cost of diesel generators decreased by 50.5%, SOFC hydrogen decreased by 89.8%, PEMFC hydrogen decreased by 79.1%, SOFC methanol decreased by 94.9%, and PEMFC methanol decreased by 98.5%. The emergency power supply scheme using $LiFePO_4$ batteries can achieve long-term continuous power supply by increasing the number of battery packs. The power backup duration and the cost of procurement costs are increased in equal proportions, and the levelized cost of energy remains unchanged throughout the life cycle, which is suitable for short-term backup. In this scenario, the LCOE of the SOFC and PEMFC are higher than that of the diesel generator and $LiFePO_4$ battery. Under the same backup power conditions, the backup power is 0-4 h, the cost of lithium iron phosphate battery is the lowest, the backup power is 5-24h, and the diesel generator cost is the lowest. The full-cycle life cost of SOFC and PEMFC as emergency power supply is higher than that of diesel generator and lithium iron phosphate battery within 24 hours of backup power. 0-13h, PEMFC hydrogen has the strongest economic competitiveness, 14-24h, SOFC methanol has the strongest economic competitiveness. The $LiFePO_4$ battery is suitable for short-term backup power, and the cost of using SOFC or PEMFC for long-term backup power is about 2.5-3.5 times that of diesel generators. In terms of 24 h power backup cost, the diesel generator is the lowest while the SOFC using hydrogen is the highest.

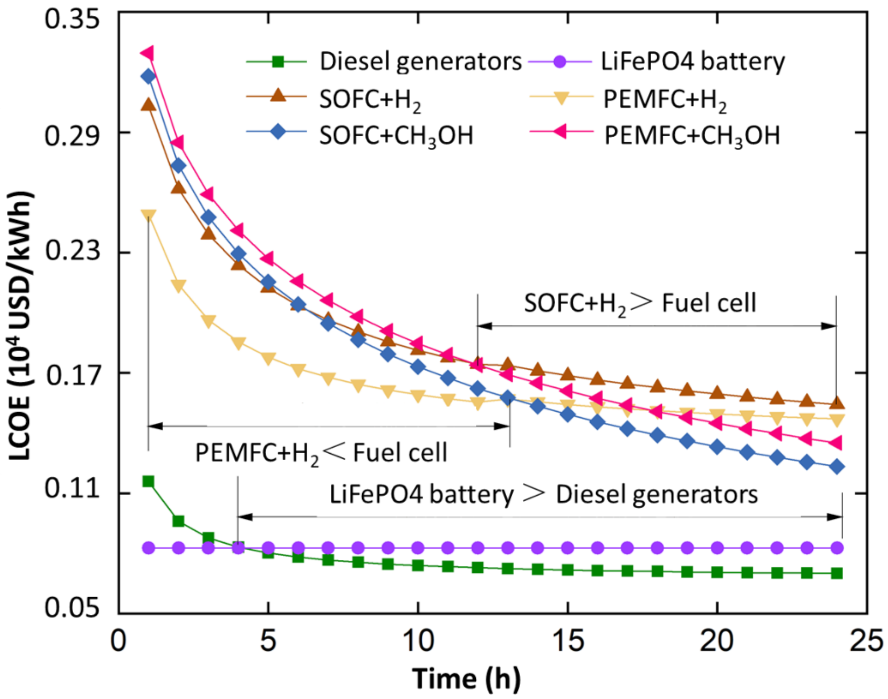

Fig. 2. Levelized cost of energy (LCOE) of emergency electrical equipment.

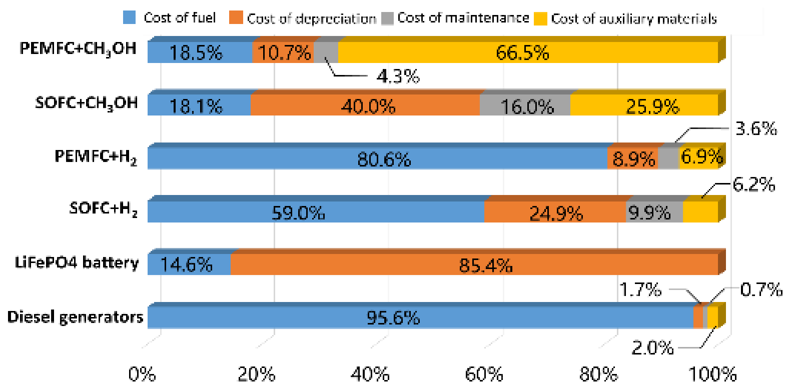

Fig. 3. Composition of levelized cost of energy.

As Figure 3 shows, diesel generators have the lowest cost at 0.48 USD/kWh, and SOFC hydrogen has the highest cost at 1.77 USD/kWh. The depreciation cost of lithium iron phosphate battery accounts for 85.37% of the total life cycle cost of electricity, which is the main factor affecting the cost. The fuel cost accounts for 58.99-95.56% of the cost of the three emergency power supply solutions of diesel generator, SOFC hydrogen and PEMFC hydrogen, which is the main factor affecting the levelized cost of energy. Using methanol as fuel can decrease the fuel cost of fuel cells. The SOFC and PEMFC emergency power systems using CH_3OH as fuel are 37.87% and 16.82% lower in cost than the emergency power system using H_2 as fuel. However, reforming reactors are required for methanol fuel cells, and those for PEMFCs using methanol require an additional function of pressure swing adsorption. This will increase the accessory cost.

4.3 Sensitivity Analysis

Changes in standards regarding production, manufacturing and environmental protection will directly affect the cost-effectiveness of emergency power. However, the influence of various factors is different. The whole life cycle cost of emergency power supply consists of four parts: the cost of auxiliary materials, maintenance cost, depreciation cost, and fuel cost. The cost of auxiliary materials is affected by the price of auxiliary materials, the frequency of backup power and the duration of backup power, the maintenance cost is affected by the price of equipment, the depreciation cost is affected by the price of equipment, the frequency of backup power, and the duration of backup power, and the cost of fuel are affected by the price of fuel, the duration of backup power, and the duration of backup power, and influence of electrical frequency. Taking the levelized cost of energy model established for emergency power for example, the sensitivity of cost to each factor is analyzed given that the price variation caused by each factor is -50-50%. As shown in Figure 4, the power backup frequency has the greatest effect, followed by backup duration, fuel price, equipment price, and accessory cost in sequence. As the accessory cost has a great effect on the levelized cost of energy only in the case of SOFC using methanol and PEMFC using methanol. This section selects fuel price, equipment price, backup power duration, backup power frequency to study the sensitivity impact of emergency power supply life cycle cost.

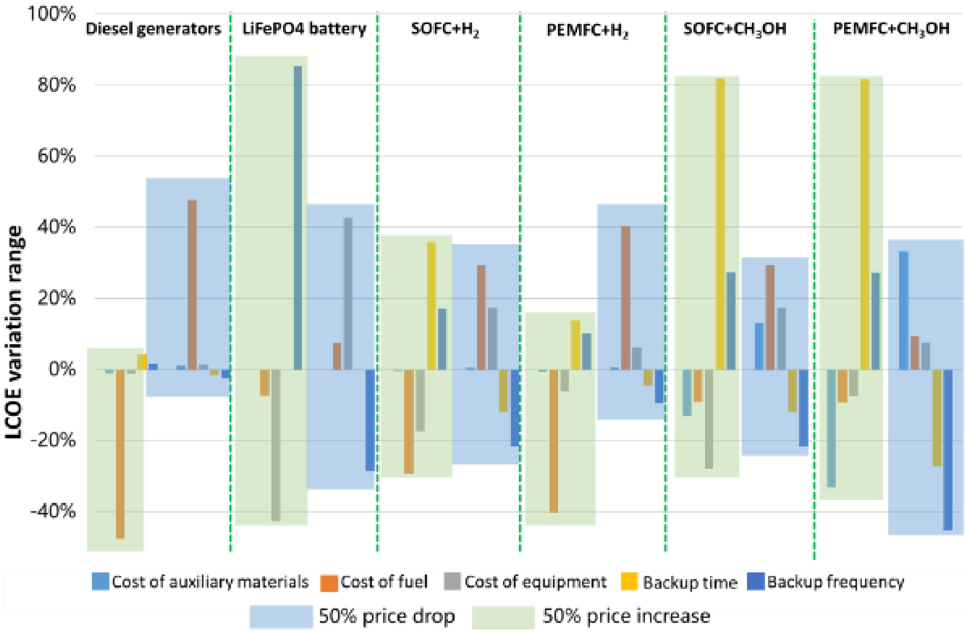

Fig. 4 Change trend of emergency power cost with sensitive parameters.

Table 5. Levelized cost of energy (LCOE) under different fuel prices.

Solution		Fuel price (USD/ unit)	LCOE (USD/kWh)	Reduction (%)
Diesel generator		0.98	0.5194	0
		0.77	0.413	20.55
SOFC	H_2	1.68	1.232	0
		0.63	0.588	52.22
	CH_3OH	0.98	1.1746	0
		0.476	1.0276	12.53
PEMFC	H_2	1.68	1.4224	0
		0.63	0.6356	55.29
	CH_3OH	0.98	1.4084	0
		0.476	1.2292	12.76

4.3.1 Fuel price

For policy control and changing situations both home and abroad, the diesel and methanol prices cannot be accurately predicted. Therefore, the average prices in the past five years are taken for analysis in this section. After considering the cost of transportation and storage, the average prices of diesel and methanol in the past five years are 0.77-0.98 USD/L and 0.476-0.98 USD/kg, respectively. The hydrogen purchase price is still high. It is expected to fall by 40-60% by 2035 after the application of several hydrogen production solutions, such as power curtailment and consumption [14]. Taking once a week, a single time of 1kW, and a backup power of 24h as an example, the full life cycle kWh cost of emergency power under the fluctuation of fuel price is shown in Table 5. The maximum cost per kWh of diesel generators in the entire life cycle is reduced by up to 20.55%. SOFC and PEMFC fueled by hydrogen decreased by 55.29%, SOFC and PEMFC fueled by methanol decreased by 12.76%. The fuel choice has a great effect on the fuel cell cost. Specifically, if a cheaper fuel is chosen, the levelized cost of energy of the fuel cell will be gradually close to that of the diesel generator and $LiFePO_4$ battery, improving the economic competitiveness of the fuel cells in the market.

4.3.2 Equipment price

Equipment price is the main factor affecting the depreciation cost of emergency power system. The development of diesel generator technology started early, the technology is mature, and the price tends to be stable. This section will not discuss it. The lithium iron phosphate battery is in the stage of technological improvement, and the cost will be further reduced through material modification and process improvement in the future. The current cost of lithium iron phosphate batteries is 112-140 USD/kWh, and it is expected to drop by 25~40% in 2030, and the cost will drop to 84 USD/kWh [14]. Electricity costs will drop by 22-35% to 0.38-0.46 USD /kWh. SOFC and PEMFC are in the stage of rapid development, and the manufacturing cost is relatively high. With the breakthrough of technical bottlenecks in the future, there is obvious room for equipment price drop. According to the development technology route of hydrogen energy and fuel cell industry, the price of PEMFC will drop by 16.67% in 2030 and by 50% in the long-term; the price of SOFC will drop by 50% in 2030 and by 82.14% in the long-term. Based on this calculation, the cost of SOFC and PEMFC as emergency power supply in the future is shown in Figure 5. Before the equipment cost fell, the SOFC hydrogen cost was the highest at 1.74 USD/kWh, and the SOFC methanol cost was the lowest at 1.08 /kWh. After long-term development, the equipment cost will be reduced, the life cycle cost of electricity of SOFC and PEMFC will be reduced, and the cost of SOFC hydrogen and SOFC methanol will decrease the most, by 28.59% and 51.29% respectively. The hydrogen cost of PEMFC is the highest at 1.46 USD /kWh, and the methanol cost of SOFC is the lowest at 0.53 USD/kWh. SOFC is more sensitive to equipment price fluctuations.

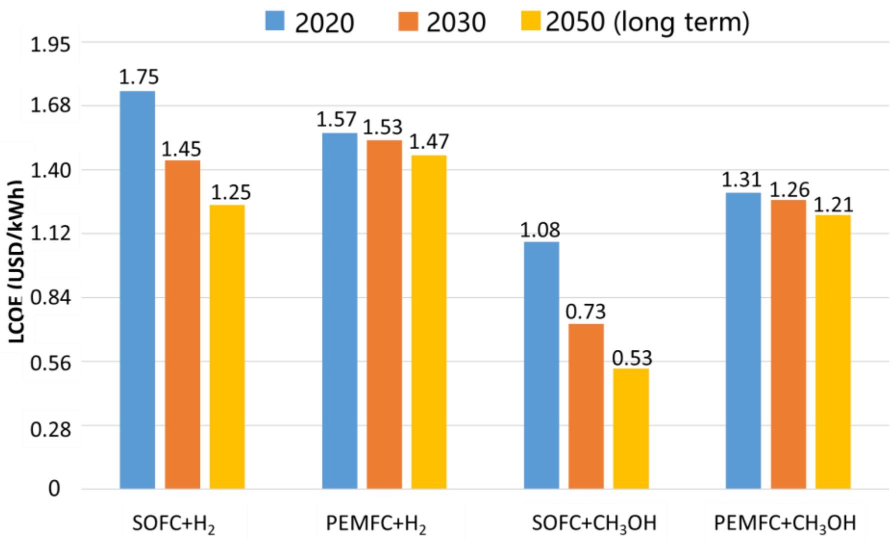

Fig. 5. Levelized cost of energy (LCOE) under equipment price.

Table 6. Levelized cost of energy (LOCE) under long time power backup cost.

Power backup (h)	LCOE (CNY/kWh)					
	Diesel generator	$LiFePO_4$ battery	SOFC		PEMFC	
			H_2	CH_3OH	H_2	CH_3OH
36	0.476	0.574	1.54	0.784	1.484	0.9492
48	0.462	0.574	1.428	0.644	1.456	0.77
60	0.462	0.574	1.372	0.546	1.428	0.658
72	0.462	0.574	1.33	0.49	1.414	0.588
80	0.462	0.574	1.316	0.462	1.414	0.56

4.3.3 Power backup duration

The emergency power is characterized by long power backup duration and is suitable for use in remote areas. With the increase of backup duration, the cost of ‘SOFC+CH_3OH’ and ‘PEMFC+ CH_3OH’, whose LOCE is most sensitive to backup duration, decreases rapidly. As shown in Table 6, when the power backup is 48h, the LCOE of SOFC methanol is gradually approaching that of lithium iron phosphate battery. When the power backup is 60h, SOFC methanol has become the most economical emergency power solution after diesel generators. When the power backup is 72h, the LCOE of

SOFC methanol is close to that of diesel generators. When the power backup is about 80h, the LCOE of SOFC methanol is comparable to that of diesel generators.

The LCOE is the lowest for short and small-scale (0-4 h) power backup using $LiFePO_4$ battery, for medium and long (5 – 80 h) power backup using diesel generator, and for long (≥ 80 h) power backup using SOFC methanol.

4.3.4 Power backup frequency

The frequency of backup power affects the total working hours of the emergency power supply. Under the assumption of a fixed service life, the influence of the frequency of backup power on the use LCOE of the emergency power supply is analyzed. As shown in Figure 6, with the increase of backup power frequency, the LCOE of the five emergency power supply schemes all decreased. The cost of PEMFC using methanol is most sensitive to the change in power backup frequency as its reforming reactor requires the function of pressure swing adsorption and thus the cost is higher. The sensitivity of SOFC using hydrogen and SOFC using methanol to the power backup frequency varies depending on the price of SOFC equipment. If the power backup frequency is increased from once a year to once a week, the service cost can be reduced by up to 49.78 USD/kWh, and only 1.3 USD/kWh. The diesel generator cost is less affected by the power backup frequency, so under high power backup frequency, it is more cost-effective to use the diesel generator as emergency power.

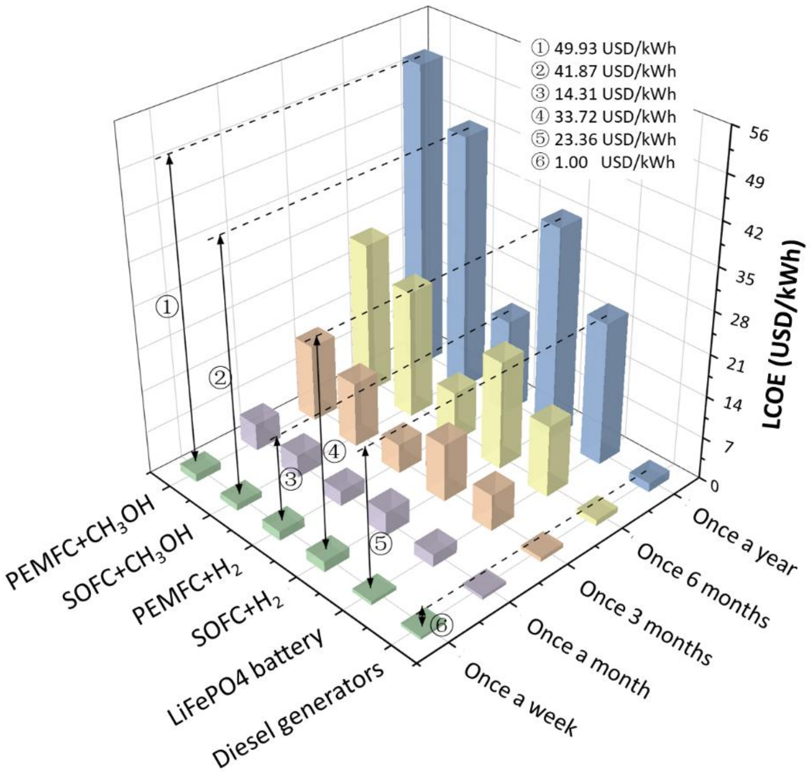

Fig. 6. Levelized cost of energy (LCOE) under different usage frequencies.

Table 7. Levelized cost of energy (LCOE) with carbon trading price.

Description		LCOE (USD/kWh) 2020	2025	2030	2050
Diesel generator		0.7	0.798	0.91	1.246
$LiFePO_4$ battery		0.35-0.546	0.252-0.518	0.154-0.504	-0.63
SOFC	H_2	1.526-1.708	1.414-1.694	1.316-1.666	0.98-1.61
	CH_3OH	1.12	1.148	1.162	1.218
PEMFC	H_2	1.344-1.512	1.232-1.498	1.134-1.484	0.798-1.428
	CH_3OH	1.344	1.372	1.386	1.47

5. COST PREDICTION

5.1 Carbon Trading

Carbon trading is a market mechanism used to reduce carbon dioxide emissions, that is, taking carbon dioxide emission rights as a commodity, thus forming the trading of carbon dioxide emission rights. Diesel generators, fuel cells fueled by methanol, generate CO_2 during operation. After the power industry is integrated into the national carbon market in 2021, the carbon trading cost also forms part of the total cost of emergency power. It is predicted that the average carbon trading price will be increased from 6.86 USD/t in 2020 to 9.94 USD/t in 2025, then to 13.02 USD/t in 2030, and further to 23.38 USD/t in 2050 [13]. Table 7 shows the LCOE under the influence of carbon trading price under the influence of carbon trading price. With the increase of carbon trading price, the cost of emergency power using diesel and methanol as fuel will increase gradually. It is estimated that the cost of the diesel generator will increase by 260% and that of SOFC using methanol and PEMFC using methanol will increase by 12% by 2050 respectively. For zero emission of the $LiFePO_4$ battery, SOFC using hydrogen, and PEMFC using hydrogen, additional income can be created by selling permits for carbon dioxide emission. Compared with the diesel generator, the $LiFePO_4$ battery will bring an additional income of 10.18 USD/kWh by 2050. However, $LiFePO_4$ batteries are unfavorable in realizing our goal of green and low-carbon development due to their high level of pollution in the early production and final recycling phases. The costs of SOFC using hydrogen and PEMFC using hydrogen are reduced by 7.74-43.84% and 8.65-49%, respectively, and they are close to the diesel generators in terms of economic competitiveness.

5.2 Costs in 2030

The 2030 emergency power costs predicted based on the changes in costs are shown in Table 8. The analysis was carried out under the condition of backup power once a week, 1 kW for a single time, and backup power for 24 hours. The fuel costs and equipment prices of lithium iron phosphate batteries, SOFC hydrogen and PEMFC hydrogen have dropped significantly, carbon transaction costs have increased, and the full-life cycle cost of electricity has decreased. The cost of lithium iron phosphate batteries is reduced by at least 60.64%, regardless of the impact of early production pollution and later recovery costs, taking diesel generators as a reference. In the case of rising carbon trading prices and lower equipment costs, lithium iron phosphate batteries will appear, and the profit from selling carbon emission rights can cover the cost of electricity. Diesel generators increased by 86.39% due to carbon transaction costs, and the increase was partly due to carbon transaction costs. The cost of the SOFC using methanol is lower than that of the PEMFC using methanol. By 2030, the economic competitiveness of diesel generators will be greatly reduced, and that of low-carbon and environmentally friendly emergency power solutions will be gradually increased. The analysis based on assumptions in this paper shows that in terms of economic competitiveness, the sequence is $LiFePO_4$ battery > PEMFC using hydrogen ≥ SOFC using hydrogen ≥ SOFC using methanol > diesel generator > PEMFC using methanol.

Table 8. 2030 emergency power cost.

Description	Diesel generator	$LiFePO_4$ battery	SOFC		PEMFC	
			H2	CH_3OH	H2	CH_3OH
Fuel (USD)[[1]]	6.3	0.6	6	4	6	4
Equipment (USD/kWh)	950	600	17850	9562.5	9562.5	17850
Carbon trading (USD/t)	3	0	0	0.7	0	0.5
LCOE (USD/kWh)	6.4	-2.5	3.6-6.1	9.4	3.4-5.9	5.9

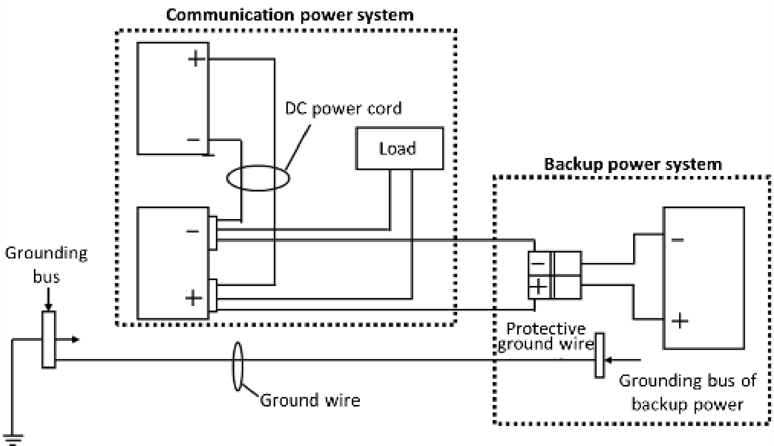

Fig. 7. Standard communication standby power supply.

6. FEASIBILITY VERIFICATION

It is expected that the fuel cell will become the optimal low-carbon economic solution for long-term continuous power backup after 2030. Taking the battery for power backup in the existing communication base stations for example, this section verifies the economic feasibility of using the fuel cell as backup power supply [15]. At present, the electrical equipment of a communication base station is generally composed of a base transceiver station and a base station controller. The base station controller specifically includes control parts such as wireless transceivers and signal processing circuits. In addition, it also includes auxiliary electrical equipment such as transmission equipment, switching power supply, computer room air conditioning, and backup lighting.

Communication power supply is an important part of communication base station infrastructure. Its main function is to provide a reliable and stable power supply for communication electrical equipment. Under normal circumstances, the AC mains is converted to DC through the inverter to directly supply power to the communication equipment. When the AC mains is disconnected and tripped, the emergency power system will continue to supply power to the communication equipment. Figure 7 shows the block diagram of the typical emergency power supply for communication.

The system input cost of 24h continuous power backup for 5 kW macro base stations is presented in Figure 8. The input cost gap among the four types of fuel cells used as emergency power is narrowed quickly with the increase of service life. The battery has a short service life, and its operation period is extended by upgrading the battery. Therefore, the change in the input cost of the battery shows a form of gentle wave. The economically optimal solution is the battery within 4 years of service and is the PEMFC using methanol within 5-10 years. The service life of the fuel cell is currently taken as 10 years and will be prolonged in the future as the technology develops and the fuel cell degrades more slowly. It is projected that the input cost of the SOFC using methanol will be significantly reduced to below that of the PEMFC after the service life is extended to 14 years. To sum up, it is feasible to use the fuel cell as emergency power for long-time (> 5 years) operation.

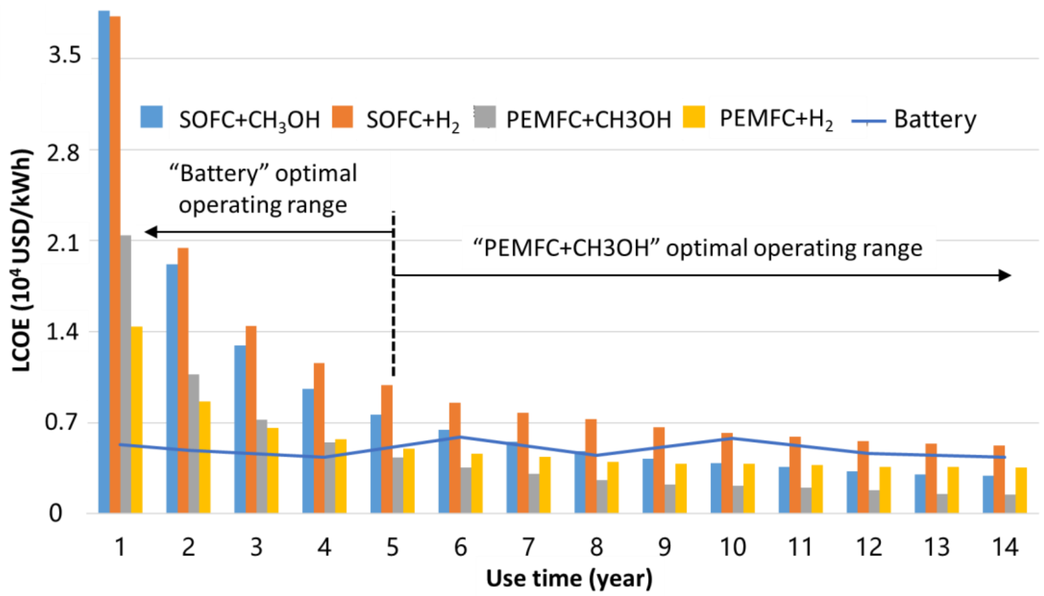

Fig. 8. System input cost comparison.

7. CONCLUSIONS

(1) The fuel price, equipment price, and power backup duration and frequency are the main factors affecting the levelized cost of energy of emergency power. The price of hydrogen and the cost of fuel cell equipment have dropped significantly, and the levelized cost of energy of SOFC hydrogen and PEMFC hydrogen is gradually approaching that of diesel engines and $LiFePO_4$ batteries. The $LiFePO_4$ battery is suitable for short and small-scale power backup, the diesel generator for medium and long (5-80 h) power backup, and the SOFC using methanol for long (≥ 80 h) power backup.

(2) In view of the carbon trading, the SOFC and PEMFC using hydrogen are expected to become the optimal low-carbon economic solution for long-term continuous power backup by 2030. In terms of the economic competitiveness, the sequence is: $LiFePO_4$ battery > PEMFC using hydrogen ≥ SOFC using hydrogen ≥ SOFC using methanol > diesel generator > PEMFC using methanol. As the usage time increases, the hourly cost of the fuel cell decreases and the future

competitiveness increases.

(3) As emergency power of communication base stations, the levelized cost of energy of the fuel cell is much higher than that of the battery in the initial stage, but after 5 years, the cost of the PEMFC is gradually reduced to below that of the battery. It is thus predicted that the SOFC using methanol will become the optimal solution extensively adopted by the communication operators.

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