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# An Improved Rule Based Energy Management Strategy for Ammonia-Hydrogen Hybrid Vehicles Utilizing BFS Optimization [#]

Zhengxian Chen[1, 2], Tianle Wu [1, 2], Weikang Li[1, 2], Wenjie Ni[1, 2], Chaosheng Huang[1, 2*], Jun Li[1, 2]
1 School of Vehicle and Mobility, Tsinghua University, Beijing, China, 100084
2 State Key Laboratory of Intelligent Green Vehicle and Mobility, Tsinghua University, Beijing, China, 100084
(Corresponding Author: huangchaosheng@tsinghua.edu.cn)

## ABSTRACT

Ammonia-hydrogen hybrid vehicles have emerged in recent years as zero carbon emissions vehicles, garnering significant attention from researchers. Currently, related research is primarily focused on ammonia-hydrogen internal combustion engines, while the overall power configuration and energy management methods for these vehicles remain underdeveloped. Therefore, this paper proposes an ammonia-hydrogen hybrid power system based on ammonia thermal decomposition technology, effectively leveraging hydrogen's high combustion speed and ammonia's high energy density. Additionally, a rule-based energy management method for this system was designed and optimized using a breadth-first search (BFS) algorithm, achieving promising results. The proposed energy management method not only provides a valuable reference for related research but also offers practical guidance for engineering applications.

**Keywords:** Ammonia, hydrogen, hybrid vehicles, energy management, BFS algorithm.

## NONMENCLATURE

| | |
|---|---|
| *Abbreviations* | |
| FC | Fuel Cell |
| SOC | State of Charge |
| *Symbols* | |
| $m$ | Mass |
| $v$ | Velocity |
| $C_{r1}$ | Rolling resistance coefficient |
| $C_{r2}$ | Rolling resistance coefficient |
| $F_{roll}$ | Rolling resistance |
| $A$ | Vehicle front surface area |
| $C_d$ | Air resistance coefficient |
| $\rho$ | Air density |
| $F_{air}$ | Air resistance |
| $\theta$ | road slope angle |
| $F_{grade}$ | Grade resistance |
| $a$ | Acceleration |
| $F_{accel}$ | Accelerating demand force |
| $F_{total}$ | Total driving force |
| $T_{wheel}$ | Wheel torque |
| $r$ | Wheel radius |
| $b$ | Fuel consumption rate |
| $\omega$ | Engine rotating speed |
| $T_e$ | Engine torque |
| $P_e$ | Engine power |
| $m_{fuel}$ | Fuel mass flow |
| $LHV_{\mathrm{fuel}}$ | Low calorific value of ammonia |
| $C_{rated}$ | Battery rated capacity |
| $t_k$ | Time point k |
| $\Delta t$ | Time interval |
| $I(t_k)$ | Current value at time k |
| $\eta_e$ | Electrical efficiency |
| $\dot{n}_{H_2}$ | Hydrogen consumption rate |
| $\Delta H$ | Enthalpy change of hydrogen combustion |
| $P_A$ | Mode switching limit |
| $P_{\mathrm{demand}}$ | Vehicle power demand |
| $\dot{P}_e$ | Engine power change rate |
| $P_{FC}$ | Fuel cell power |
| $P_{FC}^{MAX}$ | Fuel cell maximum output power |
| $\dot{P}_{FC}^{MAX}$ | Maximum change rate of fuel cell power per unit time |
| $P_b$ | Battery output power |

## 1. INTRODUCTION

With the intensification of air pollution, environmental protection has become a focal point of global attention. In 2022, global carbon dioxide emissions increased by 1.5% compared to 2021. Excessive carbon emissions can lead to numerous adverse outcomes, such as global warming[1]. In the transportation and automotive fields, reducing carbon dioxide and related pollutant emissions is also a research focus. Nowadays, significant efforts are being made in these sectors. China's transportation sector has achieved a carbon emission reduction of 12.3 million tons,

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accounting for 8.4% of the estimated carbon emissions. This is due to the extensive use of new energy and hybrid vehicles[2]. Compared to traditional single-energy vehicles, hybrid vehicles have certain advantages in terms of environmental protection and efficiency[3]. Currently, hybrid vehicles are not limited to traditional oil-electric hybrids but have also developed into various types, including fuel cell and ammonia-hydrogen hybrid vehicles.

Ammonia, as a new energy medium and fuel, is regarded as an important option for future zero-carbon fuels. It produces no carbon dioxide when burned, only generating nitrogen and water[4]. Ammonia has a higher energy density and is easier to store and transport compared to hydrogen[5]. Currently, there are also certain green ammonia solutions[6], where ammonia is produced using renewable energy without generating carbon dioxide during the production process, making it a truly clean energy source throughout its lifecycle.

However, there are certain challenges in using ammonia as a fuel in vehicles. Ammonia has issues such as being difficult to ignite and having a slow combustion rate[7]. Therefore, it has been proposed to use an ammonia-hydrogen co-combustion solution[8]. Hydrogen can be mixed with ammonia to address the ignition difficulties. The basic principle of an ammonia-hydrogen internal combustion engine, as shown in Figure 1, is similar to that of a traditional internal combustion engine, where mechanical energy is generated by burning fuel. Ammonia ($NH_3$) and hydrogen ($H_2$) are mixed in a certain ratio before entering the engine[9]. The hydrogen ignites to burn the ammonia-hydrogen mixture in the main chamber, achieving spark-assisted compression ignition[10].

The combination of hydrogen's high combustion speed and ammonia's high energy density can achieve more efficient and cleaner combustion. Researchers have conducted extensive studies on the characteristics of ammonia-hydrogen internal combustion engines. For example, M. H. Dinesh et al. indicates that a high compression ratio improves ammonia ignition performance. With an increase in compression ratio, the higher the hydrogen concentration, the more intense the combustion process, shortening the flame development and propagation time[11]. Dinesh et al. shows that the engine runs well when the hydrogen concentration is between 5% and 21%[12]. Wang et al. injected a mixture of ammonia and hydrogen (ratio of 70:30) directly into the cylinder to study its impact on engine performance. When the injection timing of the ammonia/hydrogen mixture was 12°CA BTDC and the compression ratio was 13.5, the emissions were optimal for this operating combination. It can be seen that current ammonia-hydrogen internal combustion engines are rapidly developing[13].

Additionally, on-board ammonia decomposition to generate hydrogen ensures a stable hydrogen supply. Therefore, ammonia-hydrogen co-combustion technology based on on-board hydrogen production provides broad prospects for the development of ammonia-hydrogen internal combustion engines. When combined with hybrid systems, it further enhances the overall energy efficiency of ammonia. As a zero-carbon power transportation tool, ammonia-hydrogen energy vehicles have no carbon emissions during use, which is of great significance for carbon neutrality and carbon peak[9]. All the hydrogen required by these vehicles is produced by ammonia decomposition during operation [10]. Ammonia as a hydrogen carrier partially solves the storage, transportation, and safety issues of hydrogen energy. It can be said that ammonia-hydrogen power vehicles combine the advantages of both ammonia and hydrogen energy.

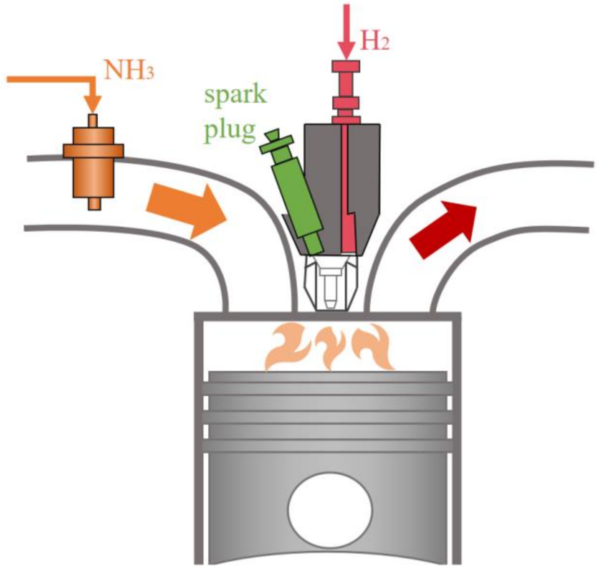

*Fig. 1 Ammonia hydrogen internal combustion engine*

Since the hydrogen in vehicles is entirely produced from ammonia, the method of ammonia decomposition is crucial to the whole system. Ammonia decomposition has several relatively mature technical routes, such as thermal decomposition and electrolysis. In automotive applications, using electricity as a secondary energy source for ammonia electrolysis reduces energy efficiency, leading to more energy consumption. Increasing the ammonia decomposition rate under lean-burn conditions and reducing the ammonia-hydrogen equivalence ratio can reduce NOx emissions and make combustion cleaner[14,15]. The heat required for ammonia thermal decomposition can be provided by the waste heat of the vehicle exhaust[10]. The ammonia-hydrogen internal combustion engine can achieve self-heating reactions using waste heat, meaning all hydrogen is produced by heating ammonia with waste heat. The hydrogen produced from ammonia decomposition can also be used in fuel cells, further enhancing the energy efficiency of the entire system.

However, there is currently no similar hybrid vehicle configuration using ammonia thermal decomposition as a hydrogen source. The ammonia-hydrogen hybrid system, as a relatively complex power system, requires an advanced Energy Management System (EMS) for power distribution and mode switching among different energy sources. Currently, there is limited research on energy management methods for ammonia-hydrogen power systems. Balancing the ammonia-hydrogen internal combustion engine, fuel cell, and power battery remains to be studied.

Existing energy management methods for hybrid vehicles can be summarized into three categories: rule-based, optimization-based, and learning-based. In practical applications, rule-based and local optimization methods are mainly used due to their low computational requirements and high stability. Many cutting-edge studies are built on the improvement and optimization of rule-based strategy. D. Shi et al. [16] introduced a reference SOC curve and SOC adaptive adjustment, achieving 44% of the fuel-saving effect of the DP algorithm with their proposed rule-based strategy. Xu Chen et al.[17] studied a Meta rule-based energy management system, which reduced the ampere-hour throughput of lithium-ion batteries by 17.0% and 9.7%, respectively. As a new power system, studying the underlying rules and logic of the ammonia-hydrogen hybrid power system is crucial for practical engineering applications and subsequent scientific research.

Therefore, this paper proposes a zero-carbon power system configuration, which is based on ammonia thermal decomposition hydrogen production and ammonia-hydrogen integration. It presents an improved rule-based energy management method for the ammonia-hydrogen hybrid power system and a parameter optimization method based on Breadth-First Search (BFS). This paper provides important references for related research.

## 2. REQUIREMENTS OF PAPER STRUCTURE

### *2.1 Calculation of demand power*

A variety of factors should be considered to calculate the vehicle demand power, including the acceleration, grade resistance, rolling resistance and air resistance of the vehicle.

a) Rolling resistance Force

Rolling resistance is the force required to overcome the friction between the tire and the road surface:

$$F_{roll} = (C_{r0} + C_{r1} \cdot v) \cdot m \cdot g$$

$F_{roll}$is the rolling resistance (Newton, N): $C_{r0}$ Is the constant part of the rolling resistance coefficient; $C_{r1}$ is the velocity dependent rolling resistance coefficient; $v$ is the speed of the vehicle in meters per second ($m/s$); $m$ is the vehicle mass in kilograms ($kg$); $g$ is the acceleration due to gravity (about $9.81\ m/s^2$).

b) air resistance

$$F_{air} = \frac{1}{2} \cdot \rho \cdot C_d \cdot A \cdot v^2$$

$\rho$ is the air density (approximately 1.225 $kg/m^3$); $C_d$ is the drag coefficient; $A$ is the frontal area of the vehicle (in square meters, $m^2$).

c) Grade resistance

$$F_{grade} = m \cdot g \cdot sin(\theta)$$

$\theta$ is the slope Angle of the road.

d) Acceleration resistance

$$F_{acce1} = m \cdot a$$

The total driving force demand $F_{total}$ is the sum of the above:

$$F_{total} = F_{roll} + F_{air} + F_{grade} + F_{accel}$$

The wheel torque demand T_wheel can be calculated from the driving force and the wheel radius as follows.

$$T_{w\hbar eel} = F_{total} \cdot r$$

### *2.2 Ammonia Engine*

The ammonia consumption rate $b$ of an ammonia engine can be regarded as a nonlinear function of the engine speed $\omega$ and torque $T_e$. The fuel consumption rate of the engine is expressed as follows[18].

$$b = f(T_e, \omega)$$

Power of the engine:

$$P_e = T_e \omega$$

Therefore, the fuel consumption rate of the engine can be expressed as a function of the engine speed and power:

$$b = f(P_e, \omega)$$

The efficiency of the ammonia engine can be calculated using the following equation:

$$\eta_{ICE} = \frac{P_e}{m_{fuel} \cdot LHV_{finel}}$$

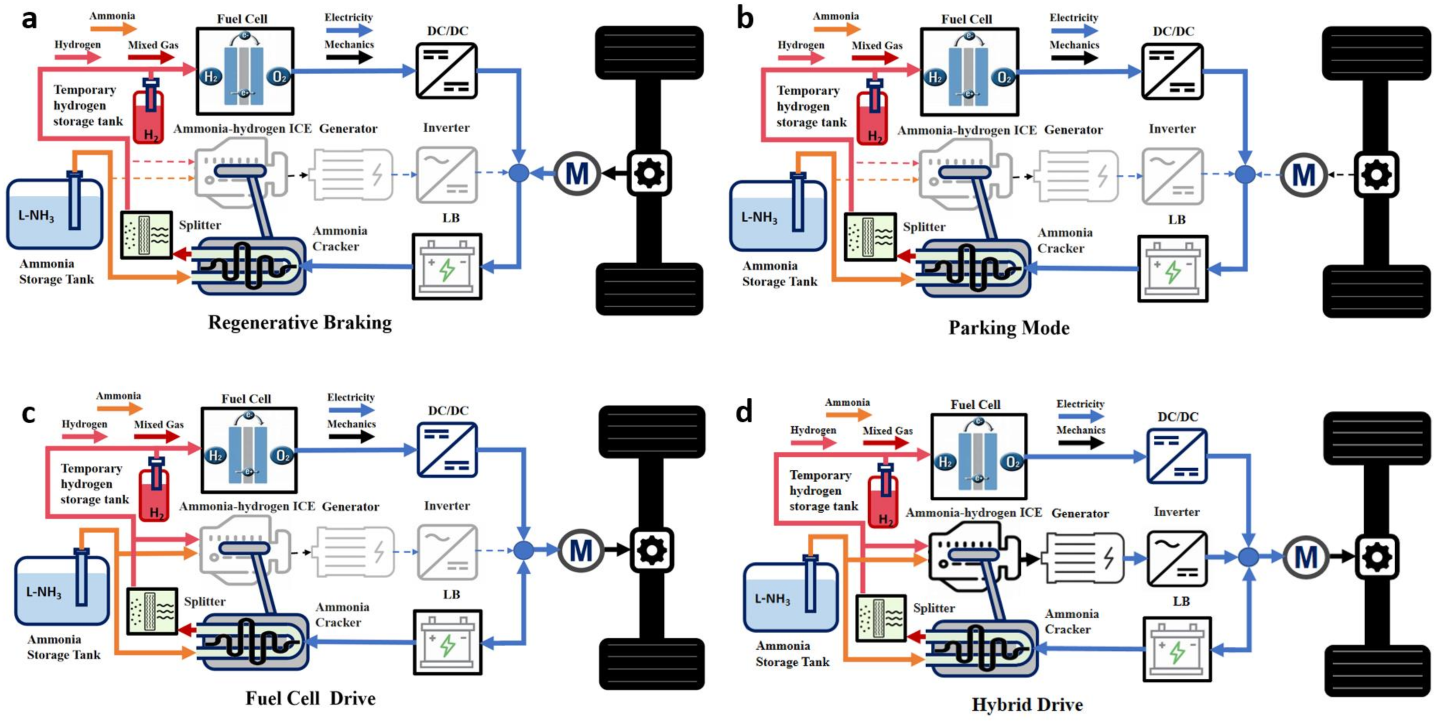

Fig. 2 Ammonia hydrogen power system

$m_{\text{fuel}}$ is fuel mass flow rate $(kg/h)$. $LHV_{\text{fuel}}$ is the low calorific value of the fuel.

### 2.3 Battery

The SOC value is estimated by integrating the current. Through the initial SOC value and the rated capacity $C_{rated}$ of the battery, the SOC update formula at discrete time points is as follows:

$$SOC(t_k) = SOC(t_{k-1}) - \frac{\Delta t \cdot I(t_k)}{C_{rated}}$$

### 2.4 Fuel cell

The efficiency of a fuel cell can be calculated by the following[19]:

$$\eta_e = \frac{P_{FC}}{\dot{n}_{H_2} \cdot \Delta H}$$

$\dot{n}_{H_2}$ is the rate of hydrogen consumption (mol/s). *$\Delta H$ is the change in enthalpy of hydrogen combustion and is about 285.83 kJ/mol.*

### 2.5 Driving Cycle

The ammonia hydrogen powertrain described in this paper is intended for heavy goods vehicles, so the CHTC-HT driving cycle(China heavy-duty commercial vehicle test cycle for heavy trucks) is used, as shown in Fig.3:

## 3. METHOD

Due to the current lack of energy management strategies for ammonia-hydrogen powered vehicles, this paper proposes an improved rule-based management for ammonia-hydrogen powered vehicles and optimizes the relevant rule parameters using a Breadth-First Search algorithm.

### 3.1 Vehicle Driving Modes

a) Regenerative Braking Mode

Regenerative braking mode involves recovering kinetic energy during deceleration and braking, converting it into electrical energy stored in the battery.

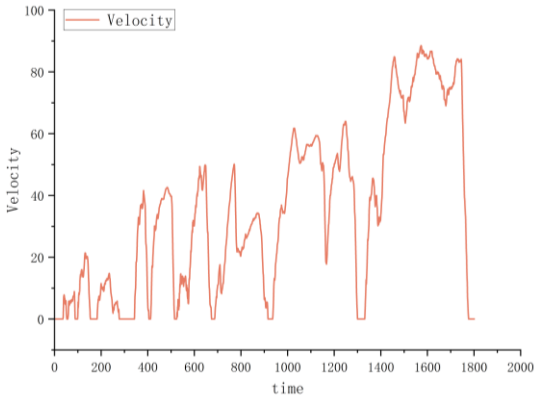

Fig. 3 Driving Cycle

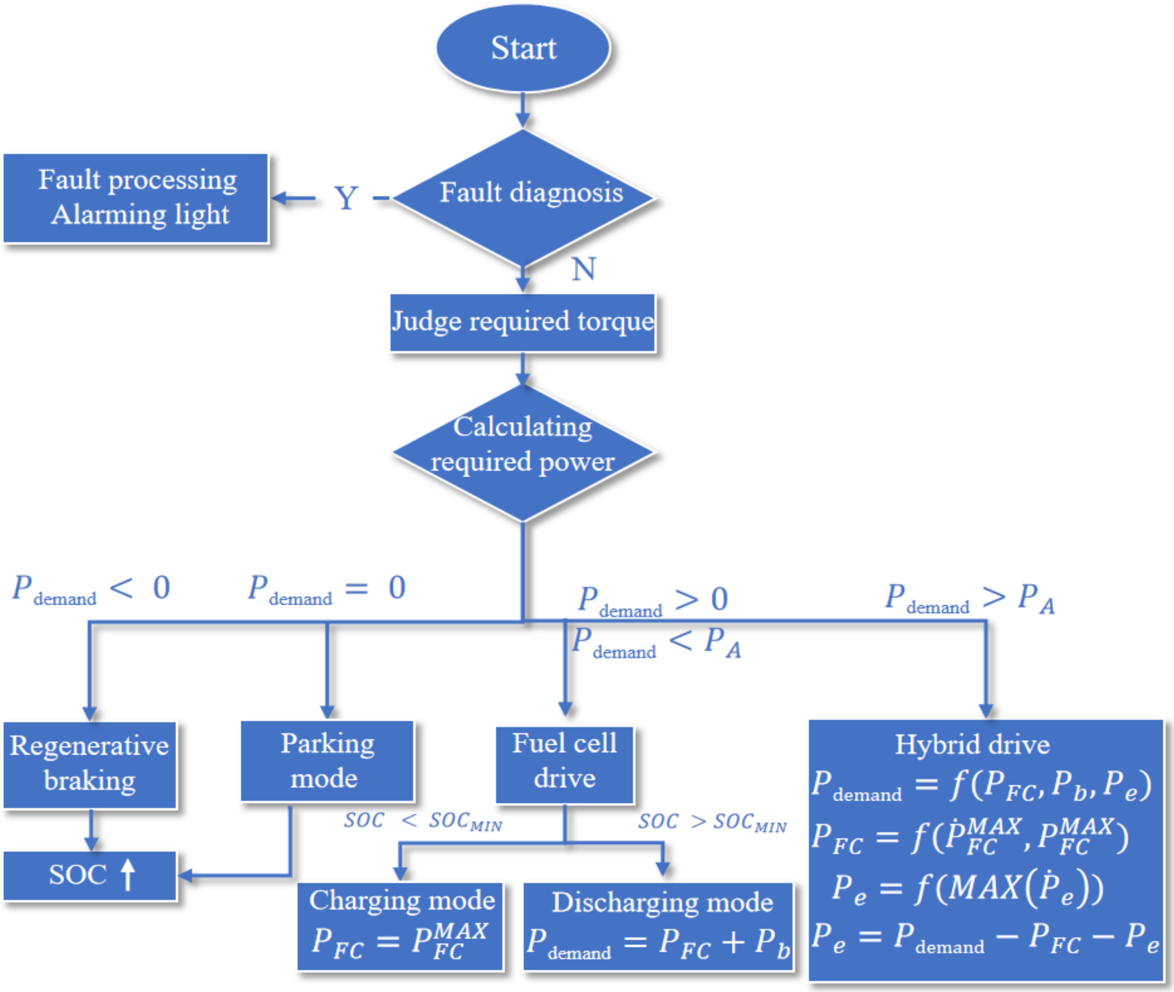

*Fig. 4 Flow chart of Rule-based EMS*

It can be approximated that when the vehicle's power demand is less than zero, the vehicle enters regenerative braking mode, as Fig.2 shown.

b) Parking Mode

In short-term parking mode, the fuel cell, which cannot continuously start and stop, operates at its minimum working limit. During this time, the fuel cell charges the power battery.

c) Hybrid Driving Mode

When the power demand exceeds the upper limit that the fuel cell can supply, the vehicle enters hybrid driving mode. At this point, the three power sources work together to provide power and drive the vehicle.

d) Fuel Cell Driving Mode

When the power demand is mainly within the working range of the fuel cell, power distribution is primarily handled by the fuel cell due to its relatively high efficiency. In response to sudden increases in power demand, the internal combustion engine and power battery supplement the power requirements.

### *3.2 Rule-Based Energy Management*

In the rule-based energy management algorithm, once the algorithm starts operating, it first conducts a fault diagnosis for the vehicle's hardware. If any issues are detected, a warning is issued, indicating the need for maintenance. Following this, the model assesses the required torque and calculates the necessary power before determining the appropriate mode.

There are four modes based on different power demands. In regenerative braking and parking modes, the system charges the power battery. When the power demand is low, the fuel cell can fully meet the requirements, and the vehicle enters the fuel cell-dominant driving mode. The internal combustion engine and lithium battery can quickly provide power to meet scenarios with sudden power demand changes, such as rapid acceleration. Finally, when the power demand exceeds the working range of the fuel cell, the vehicle adopts hybrid driving mode, where the three power sources jointly deliver power. The process is illustrated in the Fig.4.

### *3.3 BFS Optimization*

**Algorithm:** Breadth First Search for Minimizing Energy Cost

Input:
  Veh: Vehicle Property
  Cyc_data: Vehicle Velocity vs. Time
  Bat: Battery Property
**Output**:
  Optimal energy cost and efficiency

```
function CALCULATE_FITNESS(PA_limit, Eng_range, Veh, Cyc_data, Bat)
    Initialize SOC, Battery_Power, Engine_Power, Fuel_Cell_Power
    Calculate Power_required
    for each time_step do
        if Power_required <= PA_limit
            Update Battery Power, Engine Power, Fuel Cell Power
        else
            Update SOC
        PA_change_rate ← abs(Fuel Cell Powe[time_step] - Fuel Cell Powe[time_step-1])
        end if
    end for
    Energy_cost = Fuel_Cell_Power * α
    fitness ← CALCULATE_ENERGY(Energy_cost, Power_required)
    return fitness
end function

function CALCULATE_ENERGY(Energy _cost, Power_required)
    Initialize Energy _cost
    for each time_step do
        if Power_required => 0
            Update Energy _cost
        end if
    end for
    return Energy _cost
end function
for each PA_limit do
    for each Eng_range do
        fitness_score = CALCULATE_FITNESS(PA_limit, Eng_range, Veh, Cyc_data, Bat)
        if fitness_score <= lowest_fitness
            Update lowest_fitness
        end if
    end for
end for
```

*Algorithm 1: Breadth First Search for Minimizing Energy Cost*

The above code outlines the process of optimizing vehicle parameters using a battery and fuel cell hybrid system. It initializes parameters, reads driving cycle data, and calculates forces and power requirements for the vehicle. The CALCULATE_FITNESS function computes the power distribution between the battery and fuel cell based on set rules, updating SOC and fuel consumption. The CALCULATE_ENERGY function calculates the overall efficiency of the system based on total power and energy consumption. Finally, the BFS optimization framework iteratively tests different fuel cell limits and engine ranges, using the CALCULATE_FITNESS function to evaluate each configuration. The best configuration minimizes total energy consumption and fuel cell change rate.

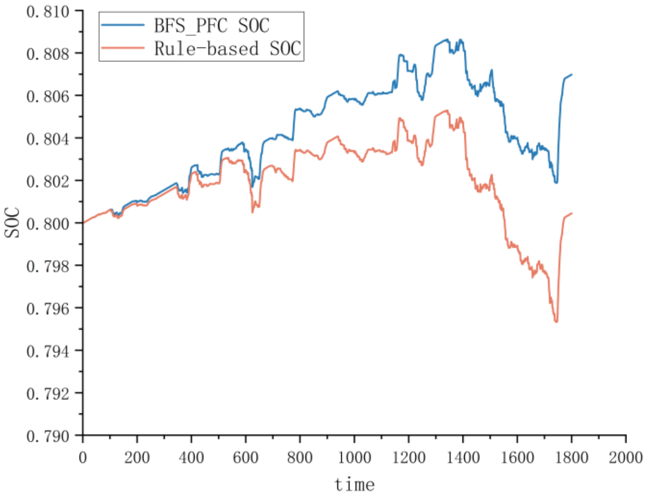

*Fig. 5 SOC changing curve*

## 4. RESULTS

The comparison of results between the rule-based method and the BFS-optimized method is shown in Fig,5, Fig 6, Table 1:

| | mode switching limit | The largest engine Upper limit of power change (kw) | efficiency | The fuel cell Power fluctuation rate |
|---|---|---|---|---|
| Rule-based | 40 | 25 | 0.37616 | 4.5864% |
| BFS | 35 | 40 | 0.38251 | 4.2976% |

*Table.1 Flow chart of Rule-based EMS*

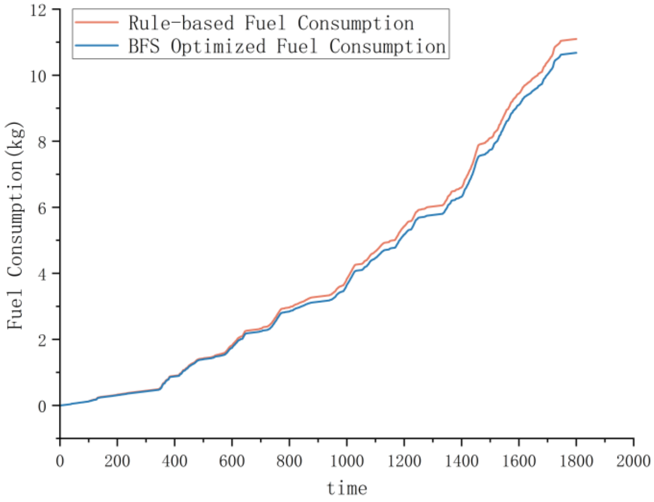

*Fig. 6 Fuel Consumption of Ammonia*

After applying BFS optimization, the system efficiency improved by approximately 1%, and the fuel cell power fluctuations decreased by 0.3%. This reduction in power fluctuations is significant for extending the lifespan of the fuel cell.

## 5. CONCLUSIONS

This paper proposes a configuration for an ammonia-hydrogen hybrid power system based on ammonia pyrolysis technology. The working modes were established according to the characteristics of the three power sources. A rule-based energy management method for the ammonia-hydrogen hybrid power system was also proposed, and its parameters were optimized using the BFS algorithm. The results indicate that the optimized energy management strategy improved energy efficiency by approximately 1% and reduced fuel cell power fluctuations by 0.3%. In the future, we plan to utilize dynamic programming algorithms and incorporate artificial intelligence methods such as deep reinforcement learning to propose more advanced energy management methods for ammonia-hydrogen power systems.

## ACKNOWLEDGEMENT

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