Comparison and Analysis of kW-Class SOFC-CHP Systems with Different Fuels

Jianzhong Zhu (jz2381@mail.tsinghua.edu.cn)
Tsinghua University https://orcid.org/0000-0001-5350-1261

Hao Meng
Tsinghua University

Minfang Han
Tsinghua University

Research

Keywords: SOFC, Combined Heat and Power, Parameter Optimization, Economic analysis

Posted Date: November 9th, 2020

DOI: https://doi.org/10.21203/rs.3.rs-102586/v1

Noname manuscript No.
(will be inserted by the editor)

Comparison and Analysis of kW-Class SOFC-CHP Systems with Different Fuels

Jianzhong Zhu · Hao Meng · Minfang Han

the date of receipt and acceptance should be inserted later

Abstract SOFC is an ideal device for developing distributed combined heat and power (CHP) systems. In this paper, kW-class SOFC system models based on semi-empirical SOFC stack model were established to optimize the systems with the aim of maximizing the system electrical efficiency. Four types of SOFC-CHP systems using different fuel including natural gas (NG), hydrogen, methanol, syngas were compared, and the relationships between key parameters and system energy efficiency were analyzed. Simlulation results show that decreasing the air inlet temperature (AIT) and increasing stack temperature will promote electrical efficiency most significantly. In addition, the operational costs of four different systems were also compared, and among which the methanol-fueled system was the lowest.

Keywords SOFC · Combined Heat and Power · Parameter Optimization · Economic analysis

1 Introduction

The distributed system combined heat and power (CHP) is a user-oriented energy consumption method, which directly provides users with various kinds of energy, can effectively improve energy efficiency by minimizing loss during transport and making full use of the waste heat. Solid oxide fuel cell (SOFC) can be used in a distributed energy system to improve energy efficiency effectively. Currently, SOFC-based distributed CHP system (SOFC-CHP) is mainly adpoted by domestic consumers, which ranges from hundreds watts to

Jianzhong, Hao Meng, Minfang Han
China State Key Laboratory of Power System, Department of Energy and Power Engineering, Tsinghua University, Beijing 100084, PR China
Tel.: +86-010-62790686
E-mail: jz2381@mail.tsinghua.edu.cn

several kilowatts. The commercial Type-S from Ene-farm in Japan is a SOFC-CHP system used for households with a rated power of 700 W [1]. SOFC can run on different fuels, hydrogen, hydrocarbon fuels such as natural gas and methanol. Although the hydrogen-fueled SOFC-CHP system may achieve higher performance and longer lifetime than hydrocarbon fuels systems, in remote areas, liquid methanol fuel is a good alternative because it is much easier to store and transport. The syngas from the water-gas reaction can also be used by SOFC directly, which is an clean and efficiency approach to gain power from coal.
Since lots of cycles can be applied for SOFC-CHP system to achieve different purpose and performance. For this reason, system simulation is a useful tool to investigate the influence of key operating parameters on different systems. In this work, several system configurations with different fuels will be selected for comparison and sensitivity analysis of critical parameters on energy efficiency will be presented. Based on the above results, parameter optimization and economic analysis will also be investigate.

2 SOFC-CHP System Configurations

2.1 Configuration 1: NG-fueled System

There are three material flows in the NG-fueled system, as shown in Fig. 1. Natural gas is firstly reformed and then flows into the anode. Water is divided into two streams, one of them supplies hot water and the other is used for steam reforming. An air compressor is used to provide preheated air to the cathode. Hydrogen separation is adopted to improve stack performance and the H_2-rich gas separated from reformed gas flows into the anode. The remaining gas is combustible and burned with cathode off-gas to provide heat at the same time. In this configuration, the anode off-gas are all recirculated back to the reformer.

2.2 Configuration 2: hydrogen-fueled System

As shown in Fig. 2, a hydrogen-fueled system with two serie-connected SOFC stacks is used to promote efficiency. The number of Cells in 2nd-stage is the half of 1st-stage. Assumming that the stack temperature and fuel utilization of these two stacks are the same. The anode off-gas of the first stack is firstly cooled down, and then further supplied to the second stack. The anode off-gas of the second stack is burned to provide heat. The cathode inlet of the second stack is the cathode off-gas of the first stage mixed with fresh air.

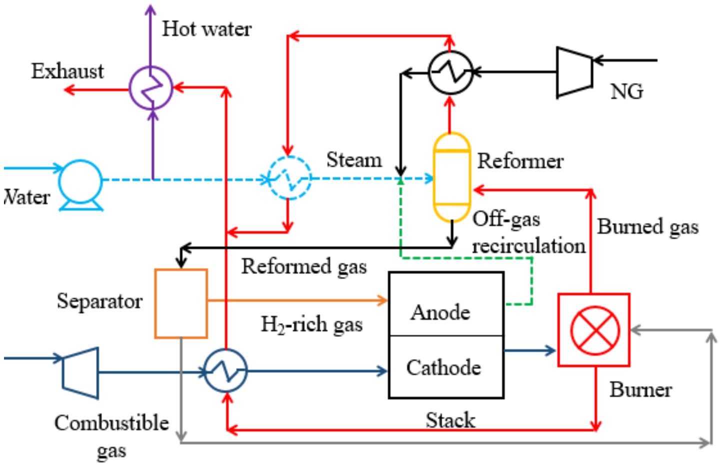

Fig. 1 NG-fueled System

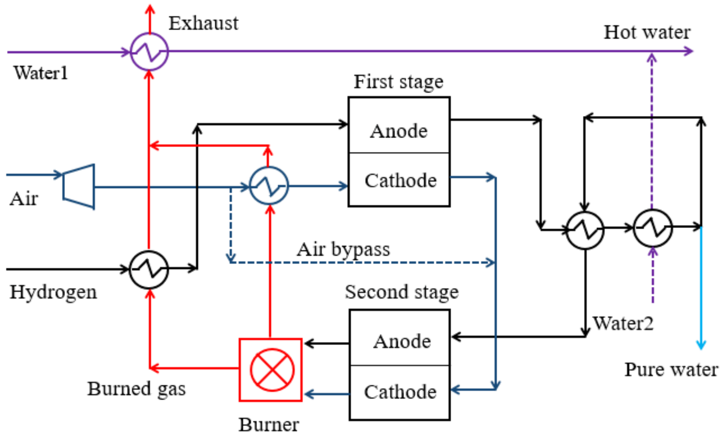

Fig. 2 Hydrogen-fueled System

2.3 Configuration 3: methanol-fueled System

The methanol-fueled system is shown in Fig. 3. In this configuration, methanol is passed into stack after steam reforming, and which is similar to the NG-fueled system. The main difference between these two systems is the different carbon content in methane and methanol. The latter one needs less steam because of lower carbon content, and steam content in recirculated off-gas is enough for the methanol reforming, which can be a great advantage when the system simplification is considered.

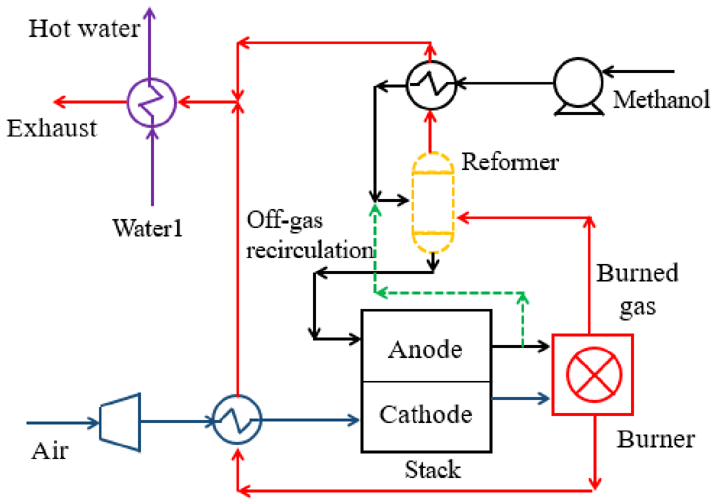

Fig. 3 Methanol-fueled System

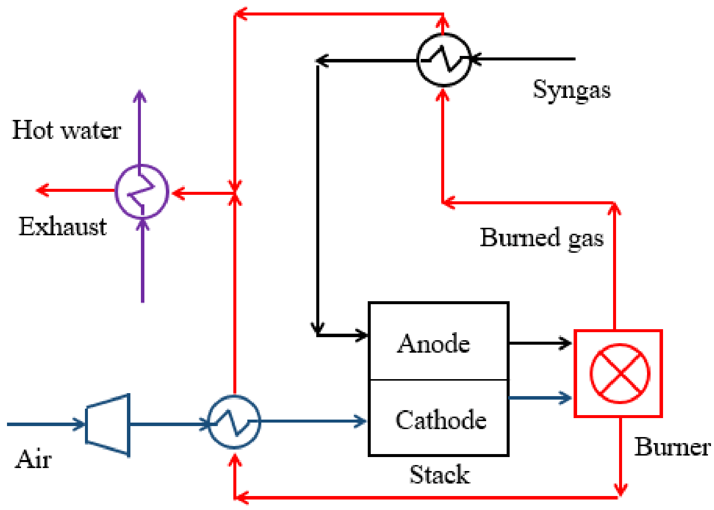

Fig. 4 Syngas-fueled System

2.4 Configuration 4: syngas-fueled System

Since solid fuels like coal can be transfered into feasible fuel for SOFC after water gas shift reaction, syngas-fueled system is also studied in this work. As shown in Fig. 4, it has a simpler system configuration compared to NG-fueled system. Syngas containing carbon monoxide and hydrogen directly enters the anode after preheating, and off-gas from both anode and cathode is burned in combuster to provide heat for the system.

Table 1 Correlation formulas and corrected constants

Parameters	Value and Expressions
Vapor relative pressure in the anode	$-0.2196Q_{fuel} + 1.1156$
Pre-exponential factor, k_a (Acm^{-2})	$5.66 * 10^{11}Q_{fuel}^{0.8064}$
Pre-exponential factor, k_c (Acm^{-2})	$3.68 * 10^{19}Q_{air}^{-0.5847}T^{-3.1686}$
Limit current density, j_L (Acm^{-2})	$5.88 * 10^{-28}e^{0.6535Q_{fuel}}T^{9.4994}$
Anode activation energy, E_a^a $(Jmol^{-1})$	$1.37 * 10^5$
Cathode activation energy, E_a^c $(Jmol^{-1})$	$1.4 * 10^5$
Pre-exponential factor, A (Ωcm^{-2})	0.002987
Constant, $B(K)$	363.57

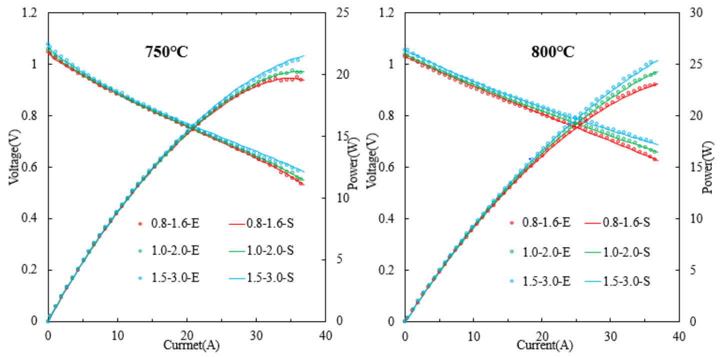

Fig. 5 Experimental and simulated results. The legends present fuel flow -air flow (L/min)-experiment or simulation

3 Modeling Approach

In this paper, a semi-empirical SOFC stack model was established based on the previous work [2]. Four correlation formulas for data fitting was summarized and four constants were adjusted according to the experiment data of a 3-cell stack experiment. The results were listed in Table 1. The validation of the semi-empirical model is validated by comparing to the experiment data, as shown in Fig. 5. The I-V-P curves calculated by the model(solid lines) is perfectly matched with the experimental result(solid dots).

4 Results and Discussion

4.1 Sensitivity Analysis

Fig. 6 shows parameter sensitivity of electricity efficiency and a relative increment of about 12% is realized by a variety of 50°C in stack temperature and AIT respectively. The temperature of reformer has a big impact on the system, a decline of 50°C can result in a reduction of 24.3%, since the maximum current is 11.6A which will lead to a shortage of hydrogen supply.

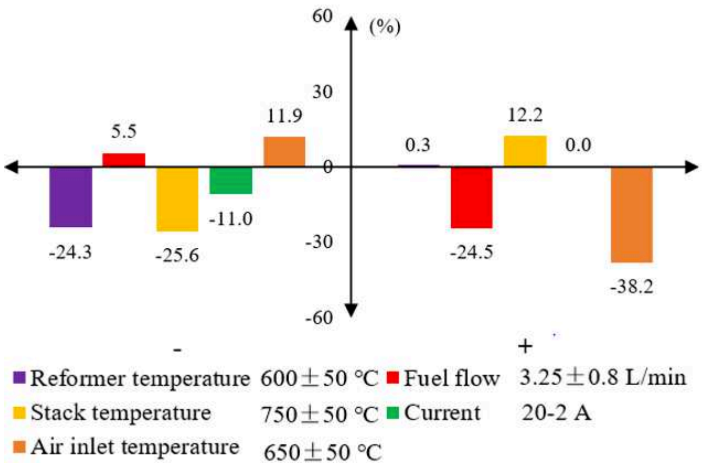

Fig. 6 Sensitivity analysis of system configuraton 1

The result of system configuration 2 is shown in Fig. 7. The fuel inlet temperature of the two stacks is set to $700°C$ while the AIT of the 2nd stage is determined by the amount of fresh air. The electrical efficiency can be improved by increasing the stack temperature or decreasing the fuel flow and AIT of the 1st stage. As shown in Fig. 8, a decrease of 164.7% is caused by an $50°C$increase in AIT, which means external power is required for system normal operation. And it is mainly due to the exothermic reforming reaction of methanol, large amount of power is needed for extra air. Aside from AIT, an increase of 26.1% is achieved if the current is lower to $18A$.
The electrical efficiency of system configuration 4 is shown in Fig. 9, a negative value of net power is obtained at an AIT of $700°C$ which is the same as methanol-fueled system. This is not only due to the heat released from electrochemical reaction but also casued by exothermic shift reaction in system configuration 4. Therefor, when raise the CO content from 50% to 70% will result in a decline of 42.3% and the maximum current is around $15.5A$ to generate less electricity.

4.2 Optimization and Economic Analysis

Parameter optimization is done based on the above sensitivity analysis, and the result is shown in Table 2. For each system, high electrical efficiency can be achieved at the low fuel flow rate, a current close to the optimal current, low AIT, and high stack temperature.

The operational modes fixing power based on heat was adopted in this work [3]. Assuming that electricity is purchased from grid and heat is obtained by NG combustion. As shown in Fig. 10, the lowest cost of $0.08\$/h$ is obtained

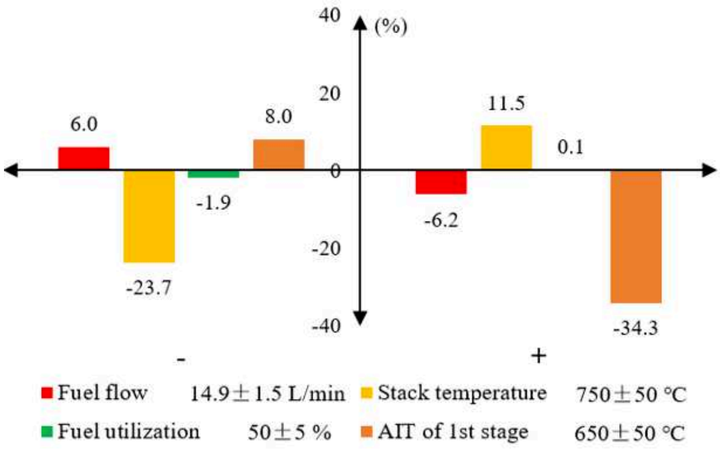

Fig. 7 Sensitivity analysis of system configuraton 2

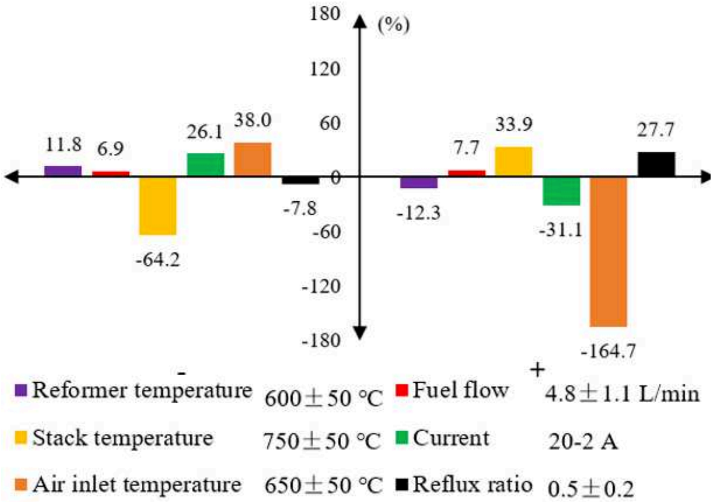

Fig. 8 Sensitivity analysis of system configuraton 3

Table 2 Optimized operational parameters of each system configuration

Parameters | System Configurations	1	2	3	4
Fuel flow (L/min)	3.25	13.44	4.8	9.3
Reformer/fuel inlet temperature ($°C$)	650	700	550	600
Air inlet temperature ($°C$)	650	650	650	650
Stack temperature($°C$)	800	800	800	800
Current(A)	18	21/19	20	20

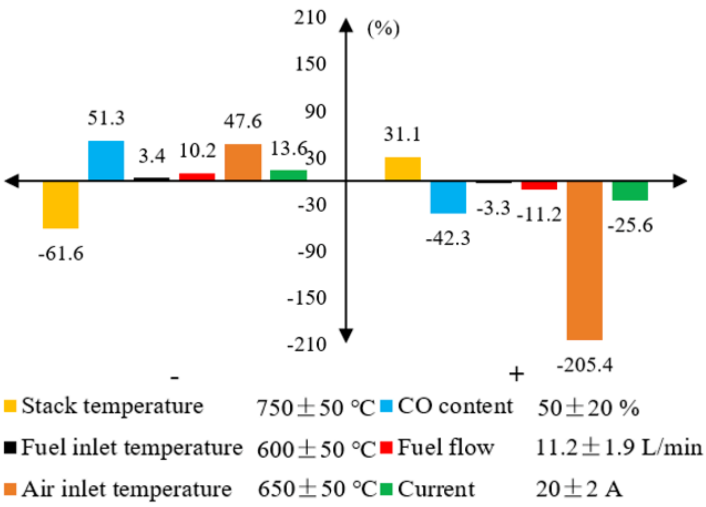

Fig. 9 Sensitivity analysis of system configuraton 4

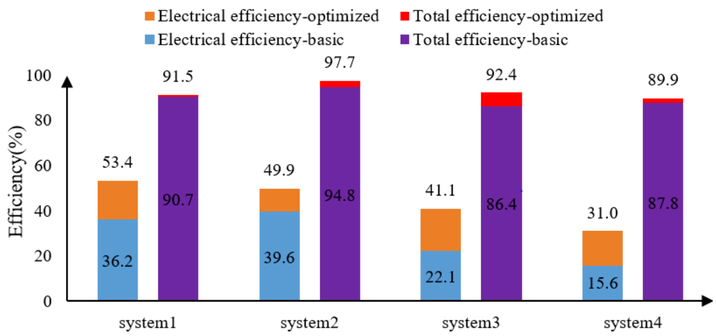

Fig. 10 Optimized electricity and total efficiency

by system configuration 1 in summer time for its high electricity efficiency. Cost of other systems except for system configuration 2 can all achieve a decrease of about 25% compared to conventional mode. In winter time, the cost of system configuration 3 and 4 is the lowest because of more heat demand, while only a decrease of 6% is achieved by system configuration 1 with part of electricity wasted. The cost of the hydrogen-fueled system is higher than the conventional for high fuel cost.

4.3 Comparison and Evaluation

Table 3 lists some of the indexes to evaluate the performance of each system. It indicates that methanol-fueled system has relatively lower complexity and operational cost while lower H2 content results in a high command for the stack.

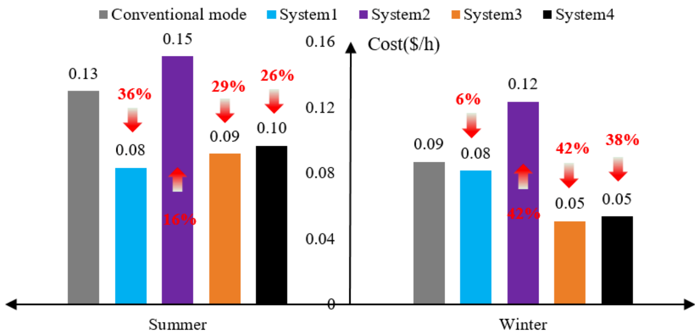

Fig. 11 The operational cost in summer and winter

Table 3 Comparison of each system configuration

Index | System Configurations	1	2	3	4
Electrical efficiency(%)	53.4	49.9	41.1	31.0
Thermal efficiency(%)	38.1	47.7	51.3	58.9
Fuel	NG	H_2	CH_3OH	$Syngas$
H_2 content in anode gas	++	++	−	−−
Complexity of system	−−	+	+	++
Cost in summer($\$/h$)	++	− − −	+	−
Cost in winter($\$/h$)	+	− − −	+ + +	++

\+ indicates a positive effect
− indicates a negative effect

For the NG-fueled system, although the system with gas separation is the most complicated, a good performance is achieved by pure H_2 supplied to the anode. Thus a low cost can be obtained when electricity is mainly required since the highest electricity efficiency and the well operating condition is realized in this system. In syngas-fueled system, a system that uses syngas as a fuel, the operational cost is low while it is applied to users with a larger amount of heat.

5 Conclusions

The highest electrical efficiency of 53.4% among the four CHP systems was achieved in the system configuration 1. The methanol-fueled system was supplied to reach the electrical efficiency of 42%. The economic analysis revealed that the usage of low-cost methanol can realize a decrease of 40% approximately compared to the conventional mode. The NG-fueled system can be operated at a low cost while electricity is mainly required. The hydrogen-fueled system with series stacks had the highest operational cost for its high cost of fuel.

Acknowledgements This work was supported by Ministry of Science and Technology, China (Most 2017YFB0601901).

Conflict of interest

The authors declare that they have no conflict of interest.

References

1. Yoda M, Inoue S, Takuwa Y, et al. Development and Commercialization of New Residential SOFC CHP System[J]. ECS Transactions, 2017, 78(1): 125-132.
2. Shi W , Han M . A conceptual design of catalytic gasification fuel cell hybrid power plant with oxygen transfer membrane[J]. Journal of Power Sources, 2017, 361:211-220.
3. $http : //home.osakagas.co.jp/search_buy/enefarm/about/convenience.html$

Figures

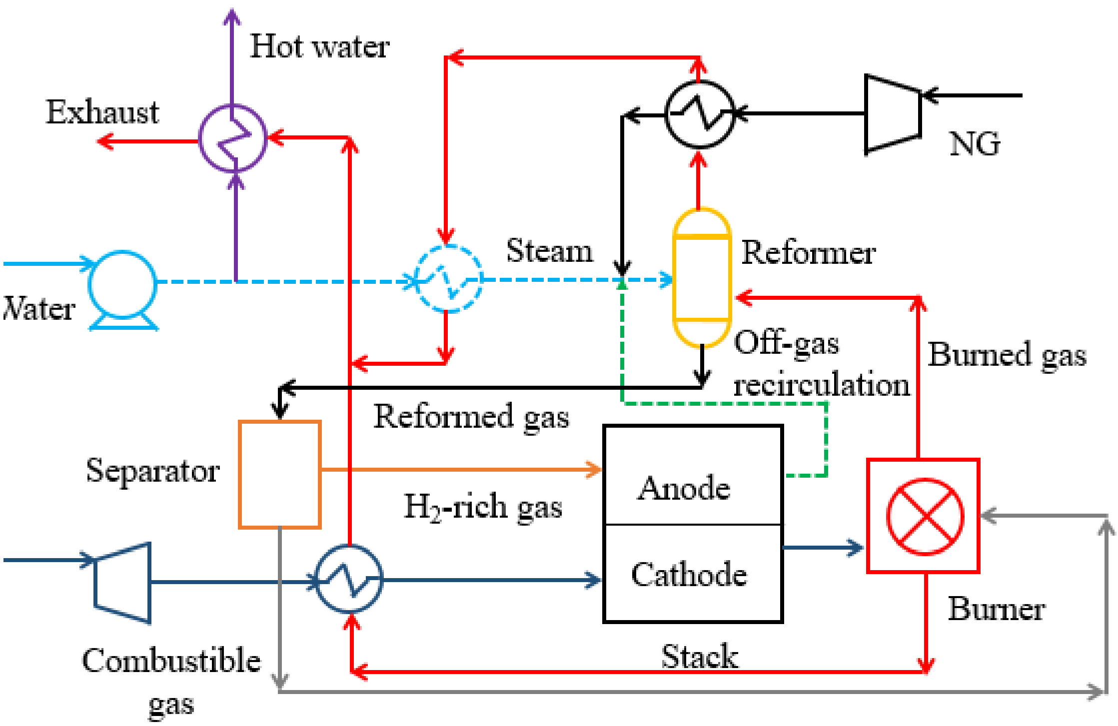

Figure 1

NG-fueled System

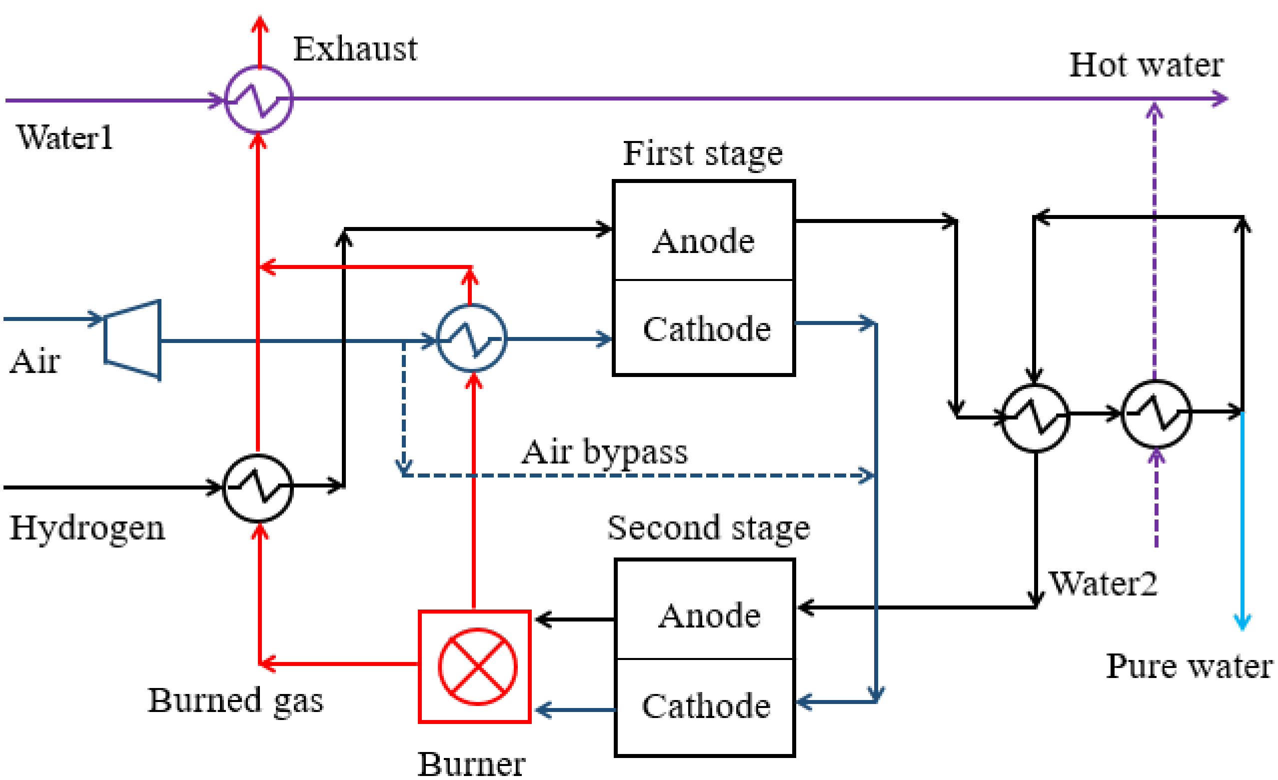

Figure 2

Hydrogen-fueled System

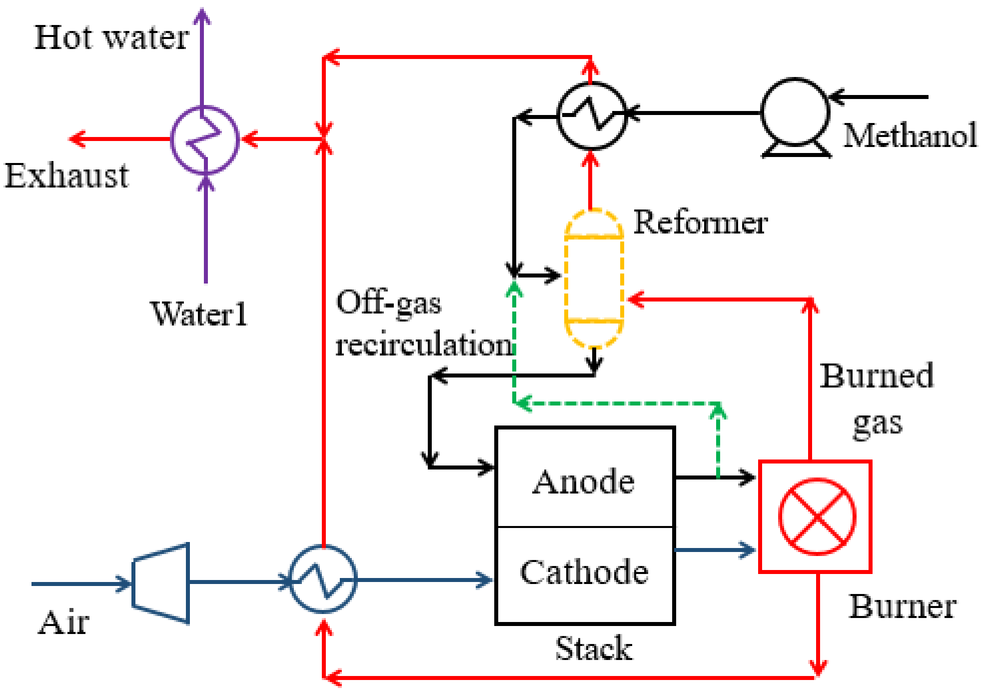

Figure 3

Methanol-fueled System

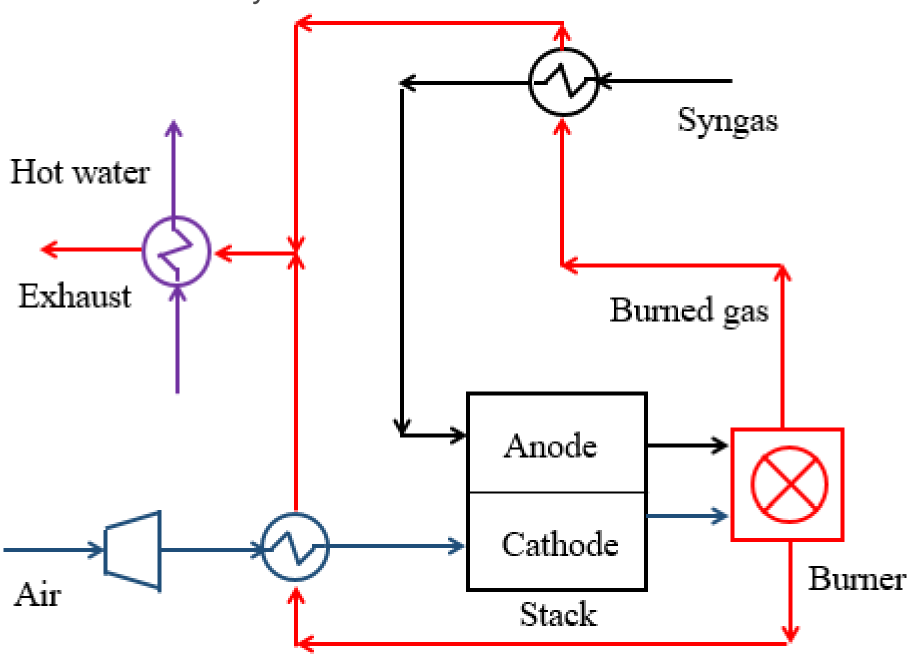

Figure 4

Syngas-fueled System

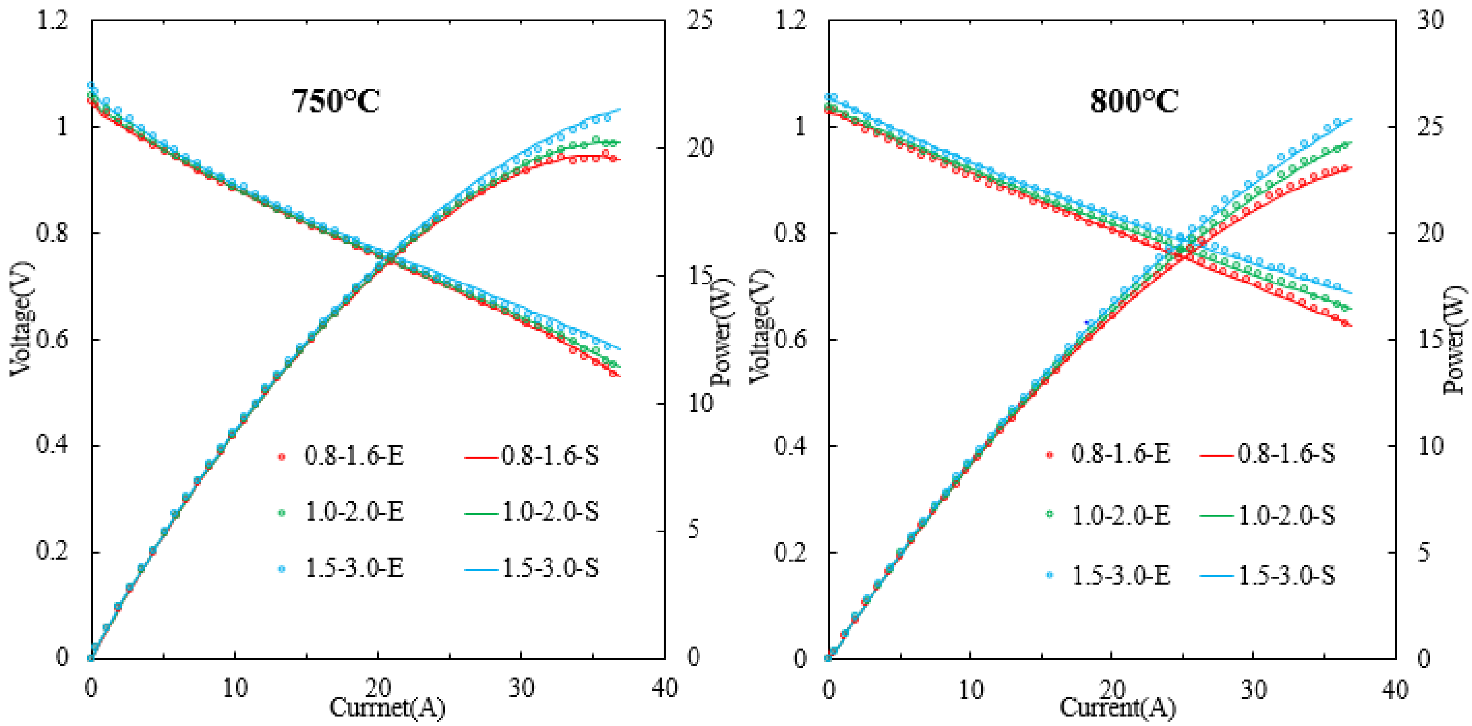

Figure 5

Experimental and simulated results. The legends present fuel flow -air flow (L/min)- experiment or simulation

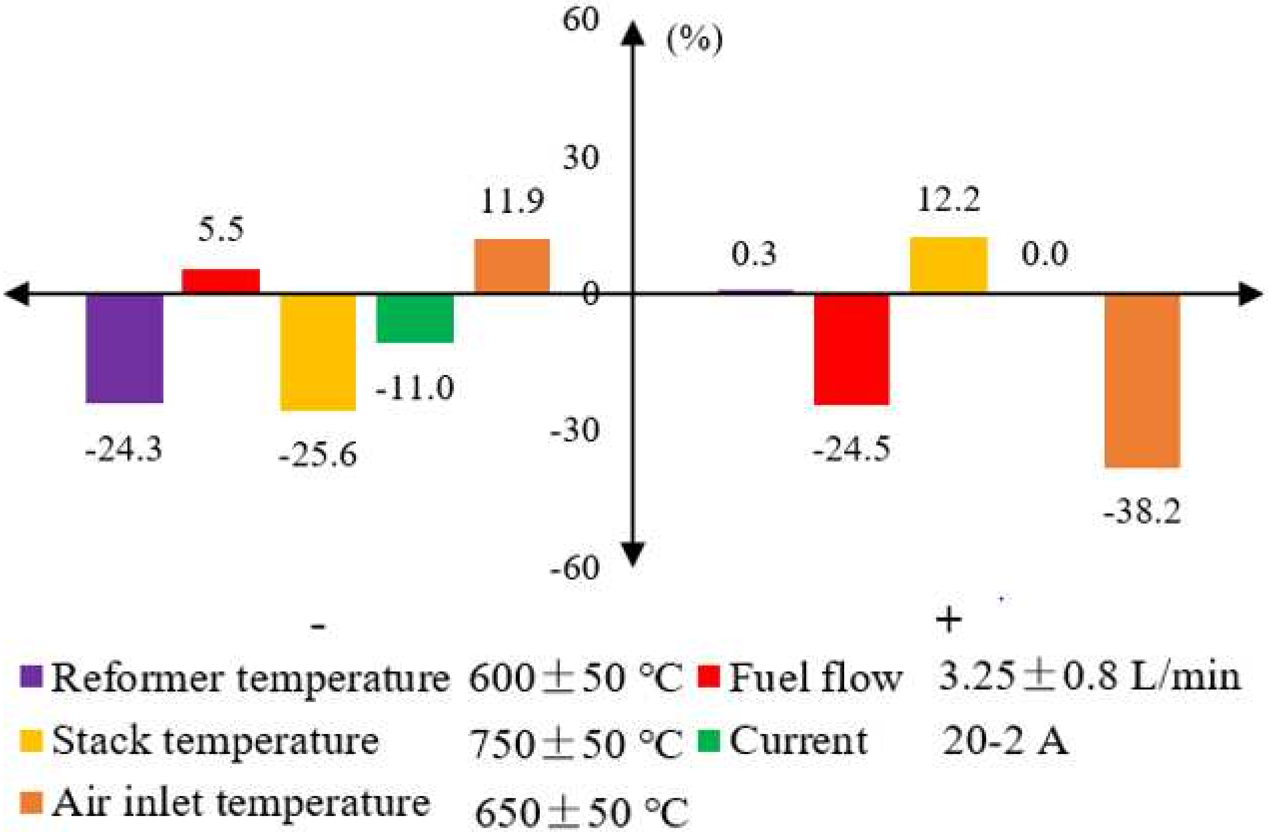

Figure 6

Sensitivity analysis of system configuration 1

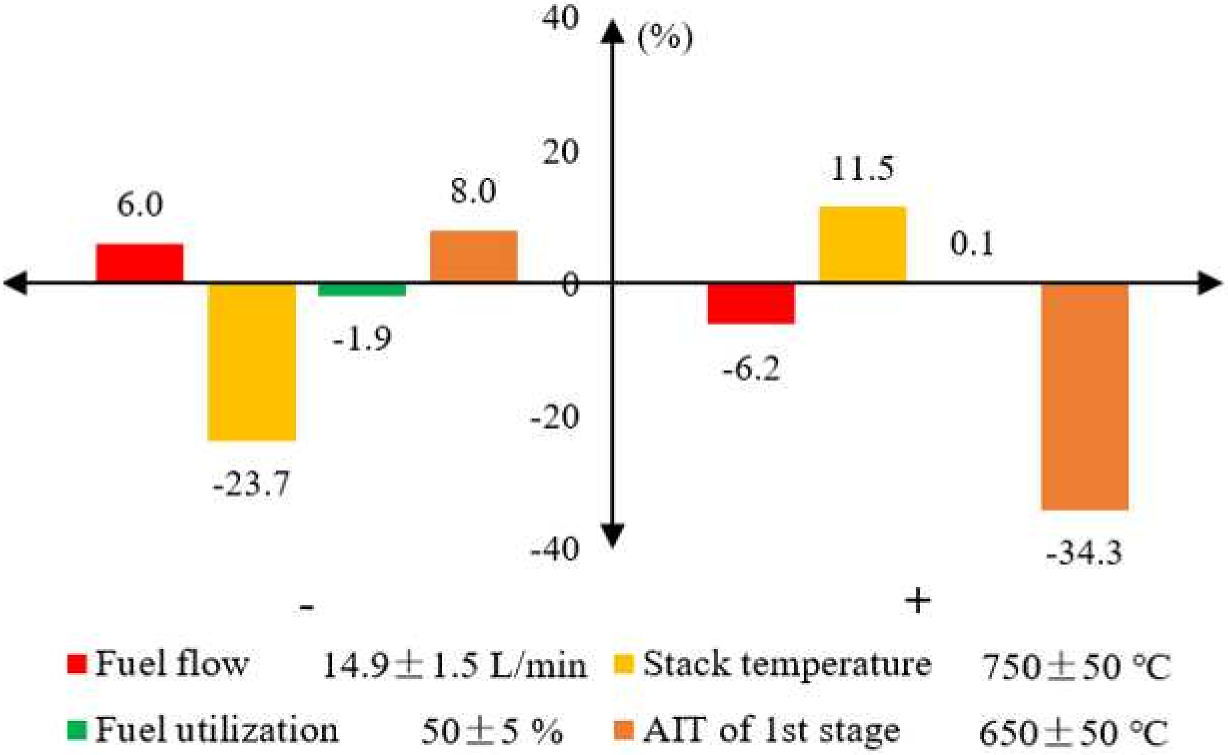

Figure 7

Sensitivity analysis of system configuration 2

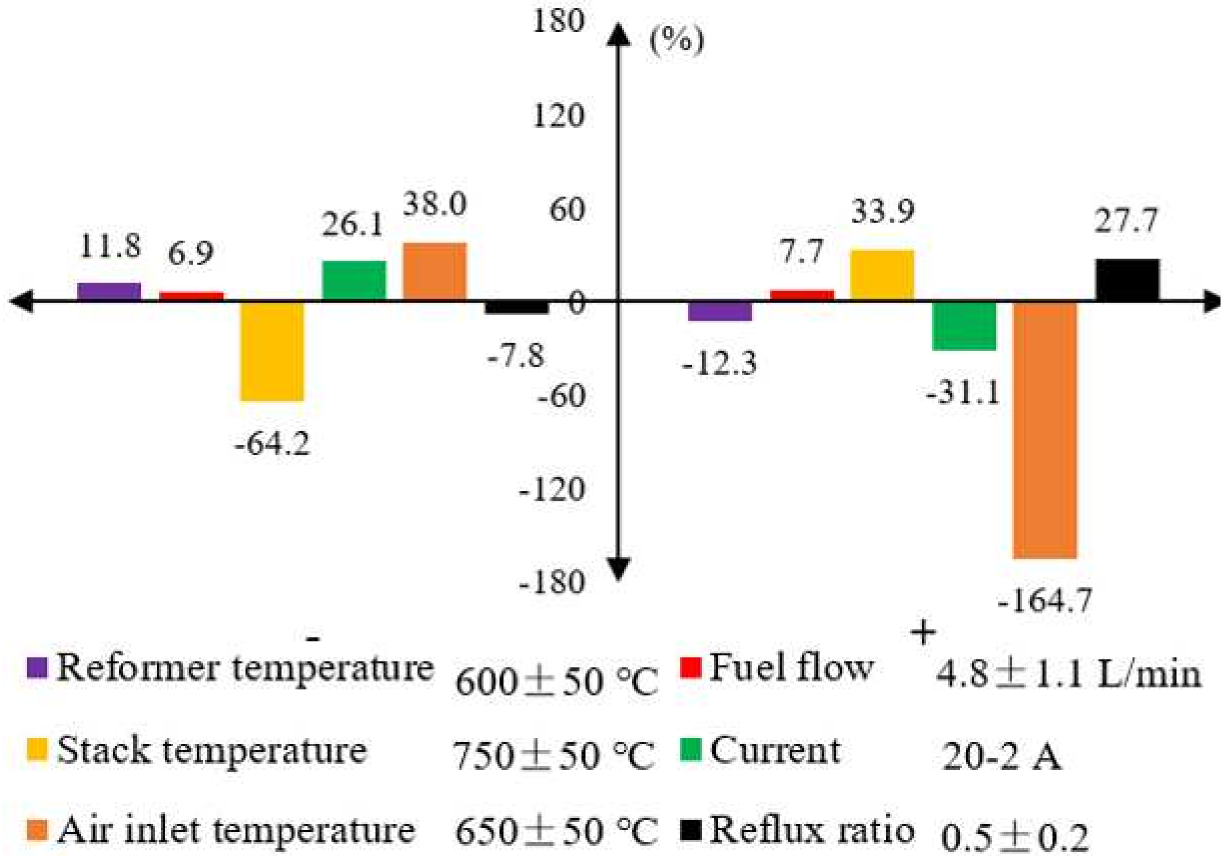

Figure 8

Sensitivity analysis of system configuration 3

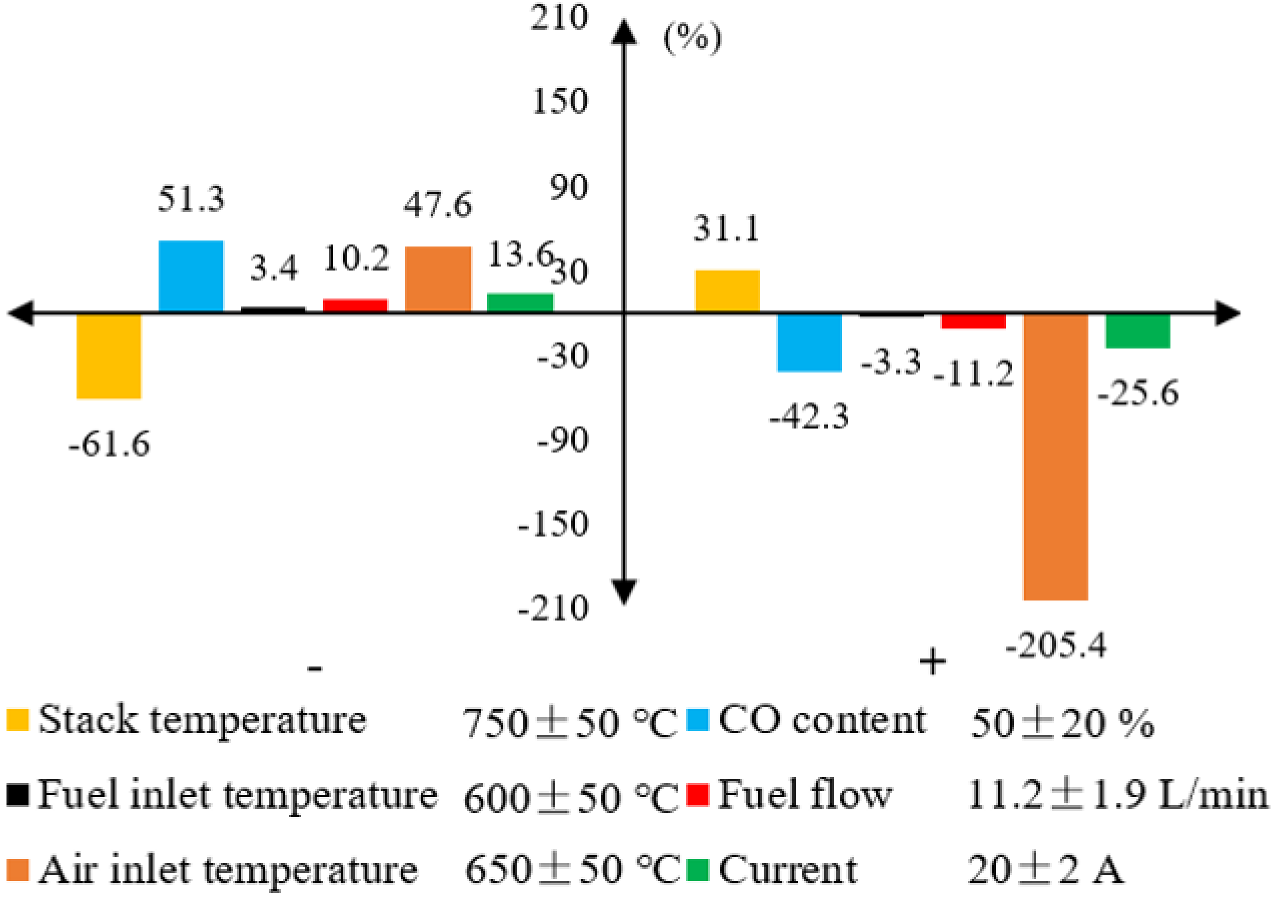

Figure 9

Sensitivity analysis of system configuration 4

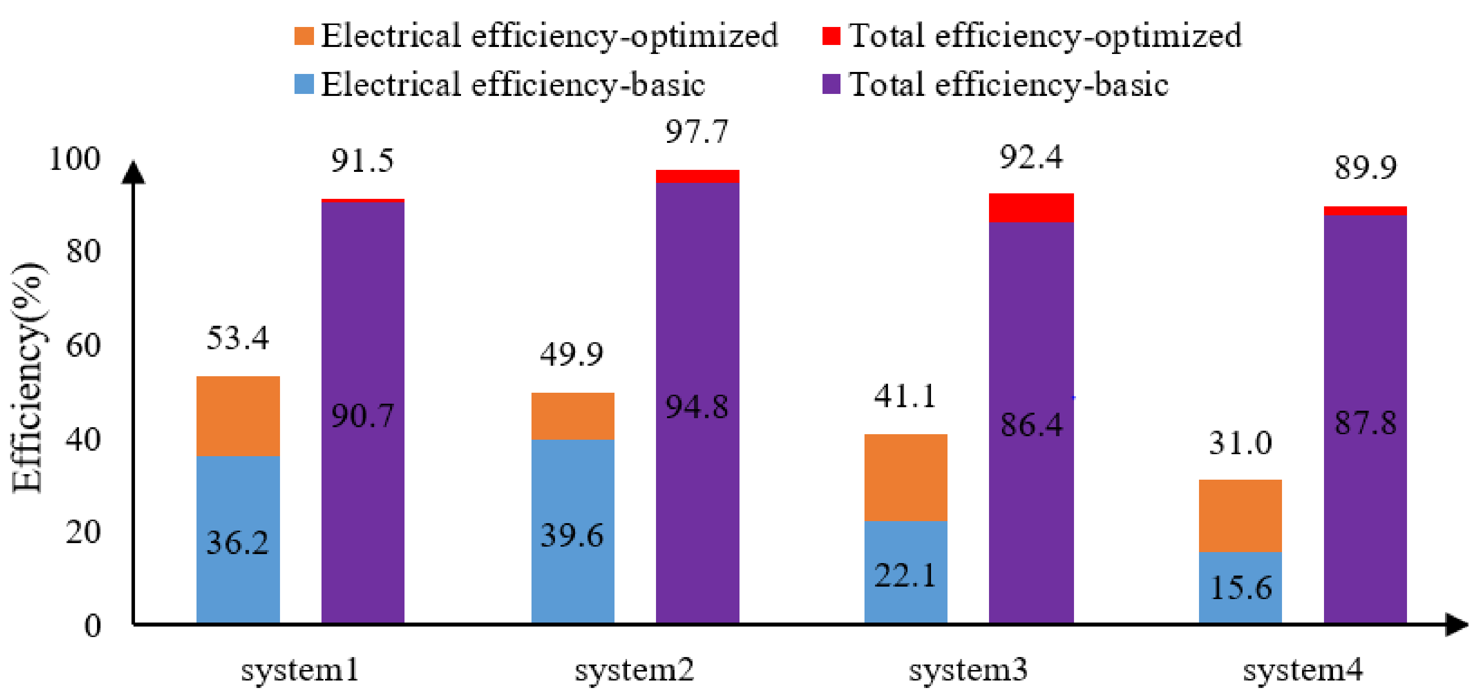

Figure 10

Optimized electricity and total efficiency

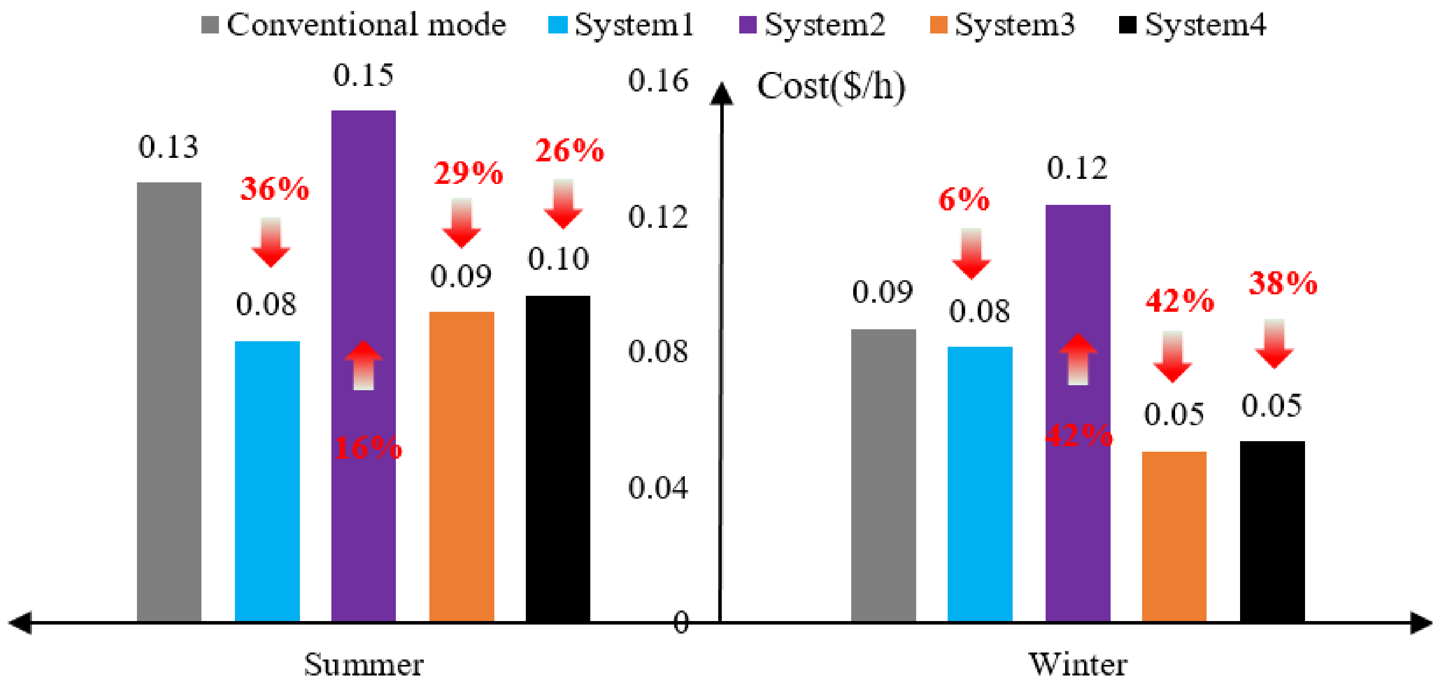

Figure 11

The operational cost in summer and winter