

## Article

# Economic Analysis of Solid Oxide Fuel Cell Systems Utilizing Natural Gas as Fuel

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**Abstract:** Solid oxide fuel cell power generation systems are devices that utilize solid electrolytes to transfer ions for electrochemical energy conversion. A wide range of gases can be used as fuel gas, including hydrogen, natural gas, and carbon monoxide. Considering the high cost of pure hydrogen, hydrogen production from natural gas reforming has become a hot research area. In this study, the 4F-LCA method was employed to construct an evaluation framework, with a particular emphasis on the cost analysis of solid oxide fuel cell power generation systems, and uses a bottom-up approach to build a system economic analysis model to visualize the major costs involved in the system. An economic benefit analysis and sensitivity analysis were carried out for the 2 kW natural gas solid oxide fuel cell as a case by taking the financial net present value (NPV), internal rate of return (IRR) and payback period into account. In this study, the investment cost and payback period of a 2 kW solid oxide fuel cell system are obtained, which can provide a reference for the project construction and operation of solid oxide fuel cell systems.

**Keywords:** solid oxide fuel cell system; economic analysis; sensitivity analysis; natural gas



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## 1. Introduction

The overconsumption of fossil energy and the continued increase in global greenhouse gas emissions have reached a new peak. In response, there is an opportunity for the diversified application of green renewable energy to address these challenges. The *National Development and Reform Commission. China maps 2021–2035 plan on hydrogen energy development*, which was promulgated by China in 2022, clarifies the strategic positioning of hydrogen energy in China's green and low-carbon energy transition [1]. Hydrogen is a high-calorific-value clean energy source that can be combusted to produce thermal and kinetic energy, as well as electrical and thermal energy through fuel cells (FCs) [2]. A solid oxide fuel cell (SOFC) system is based on ceramic electrolyte and utilizes gas-reforming hydrogen for electrochemical energy conversion. It operates at temperatures ranging from 600 to 1000 °C [3] and boasts significantly higher power generation efficiency compared to other FCs [4]. The potential applications of SOFC systems include distributed power plants, commercial buildings, cogeneration systems, and offshore marine auxiliary power units [5–8]. While the commercialization of SOFC power generation systems in foreign nations has reached maturity, domestic technology still faces challenges [8]. Drawing on the existing research foundation and foreign results [9–11], an economic analysis of the SOFC system combined with practical cases will provide a theoretical framework for company cost reduction, as well as certain economic, environmental, and social benefits. This work outlines the primary production workflow for SOFC systems, establishes a model for the economic flow analysis of the system [12,13], and illustrates the cost analysis of economic evaluation indicators while considering factors affecting performance such as sensitivity and economic benefit analyses. The study focuses on a 2 kW SOFC system powered by

pipeline natural gas. Additionally, it determines key economic elements while utilizing China's carbon trading scheme to calculate greenhouse gas emission reductions' impact on the main evaluation indexes.

## 2. Solid Oxide Fuel Cell System

The research object of this paper is a newly made SOFC power generation system with a constant output power of 2 kW (Wuxi, China). This product mainly includes the following processes:

- Production of ancillary equipment which includes choosing various steel types and forging in accordance with the design device's dimensions. The reformer, desulphurization tanks, static mixing tanks, and other components were designed by the project unit independently;
- Pre-treatment of the fuel gas, the desulphurization of the raw gas using adsorbents;
- Single cell production, a complex manufacturing process that can be broken down into the following stages: powder treatment, paste printing, and monomer sintering [14];
- Cell stack production, in which the cut cell monomers are assembled with bipolar plates and seals;
- Operation of the cell stack system, in which the output power of the stack and the tail gas emission are analyzed.

Prior to the study, we conducted a literature review (Table 1) of SOFC life cycle cost assessments [15–24]. In the past few decades, the economic analysis of SOFCs has focused on the thermal economic research of SOFC and hybrid power systems, but seldom on life cycle cost and the profit analysis of the market potential. The team of Andrea L. Facci [15] used two strategies of minimum cost control and minimum PEC control to carry out 25 kW and 40 kW SOFC-based CHCP plants' economic potential and analyzed three SOFC cost scenarios. The team of Moein Shamoushaki [16] studied the sensitivity analysis of change in objective functions with regard to the SOFC-GT fuel unit cost, and their economic indexes were cost per unit of time, fuel cost rate, exergy destruction cost, and payback period time. The team of R. Napoli [17] conducted economic analysis by comparing the net present value of 1 kW PEMFC and SOFC systems. The annualized cost, net present value, internal rate of return, and payback period time were mostly used in different sizes of high-power SOFC-GT systems by the researchers, Mousa Meratizaman [21], Valentina Zaccaria [22], Khalid Al-Khori [23], and Beneta Eisavi [24]. Similar to Ettore Bompard's research [20] on 5 kW household systems, we aimed to study the economic features of the newly made 2 kW system for residential application.

**Table 1.** Economic analysis of the SOFC—literature survey.

|                        | Sizes        | Form                                       | Index                 |                       |                         |                     |
|------------------------|--------------|--------------------------------------------|-----------------------|-----------------------|-------------------------|---------------------|
| Andrea L. Facci [15]   | 25 kW /40 kW | SOFC-based CHCP plant                      | Cost minimization     | PEC minimization      | Payback period time     | -                   |
| Moein Shamoushaki [16] | -            | SOFC-GT                                    | Cost per unit of time | fuel cost rate        | Exergy destruction cost | Payback period time |
| R. Napoli [17]         | 1 kW         | PEMFC and SOFC micro-CHP fuel cell systems | Net present value     | -                     | -                       | -                   |
| Mehdi Aminyavari [18]  | -            | SOFC-GT hybrid power plant                 | Cost per unit of time | The unit cost of fuel | -                       | -                   |

Table 1. Cont.

|                         | Sizes      | Form                                             | Index                                                     |                                     |                             |   |
|-------------------------|------------|--------------------------------------------------|-----------------------------------------------------------|-------------------------------------|-----------------------------|---|
| A Khandkar [19]         | 25 kW      | Natural gas-fueled SOFC power system             | Total capital cost                                        | Operating cost                      | -                           | - |
| Ettore Bompard [20]     | 5 kW       | High-temperature SOFC systems                    | Net present value                                         | Internal Rate of Return             | -                           | - |
| Mousa Meratizaman [21]  | 11–42.9 kW | SOFC-GT                                          | Annualized capital/replacement/maintenance/operating cost | Net present value                   | Levelized cost of product   | - |
| Valentina Zaccaria [22] | 330 kW     | SOFC-GT                                          | Payback Period                                            | Net Present Value                   | Internal Rate of Return     | - |
| Khalid Al-Khori [23]    | 20 MW      | Combined steam and power system with a SOFC unit | Net present value                                         | Internal Rate of Return             | Return of Investment        | - |
| Beneta Eisavi [24]      | -          | SOFC-based hybrid systems                        | Total cost                                                | Annual levelized capital investment | The capital recovery factor | - |

### 3. Materials and Methods

In this study, the 4F-LCA methodology [25] was applied to build an evaluation framework and focus on the economic flow (Figure 1).

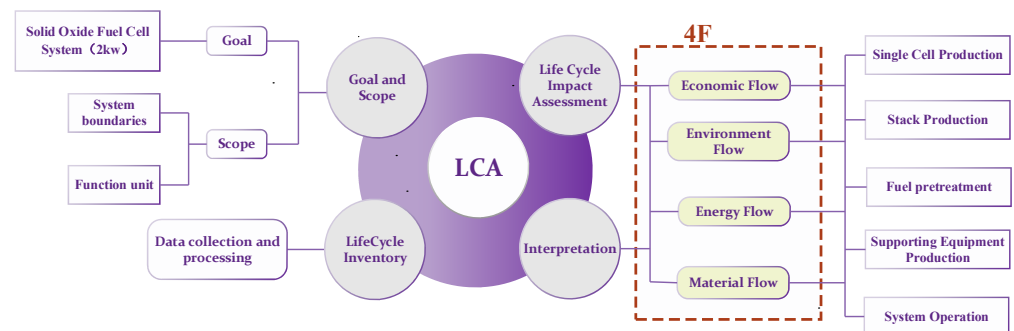


Figure 1. 4F-LCA evaluation frame diagram.

The whole system consumption cost of producing an SOFC system mainly includes the raw material input and pretreatment cost, initial investment in production cell equipment, plant operation cost, equipment maintenance cost, and labour cost, and the cost data were obtained through conducting questionnaire surveys with business managers.

#### 3.1. Goal and Scope

The system economic flow analysis model is shown in Figure 2. In this study, the economic flow analysis adopted a bottom-up method, starting from raw material, equipment, land, labour, and utility capital inputs, selecting the appropriate economic indicators for evaluation.

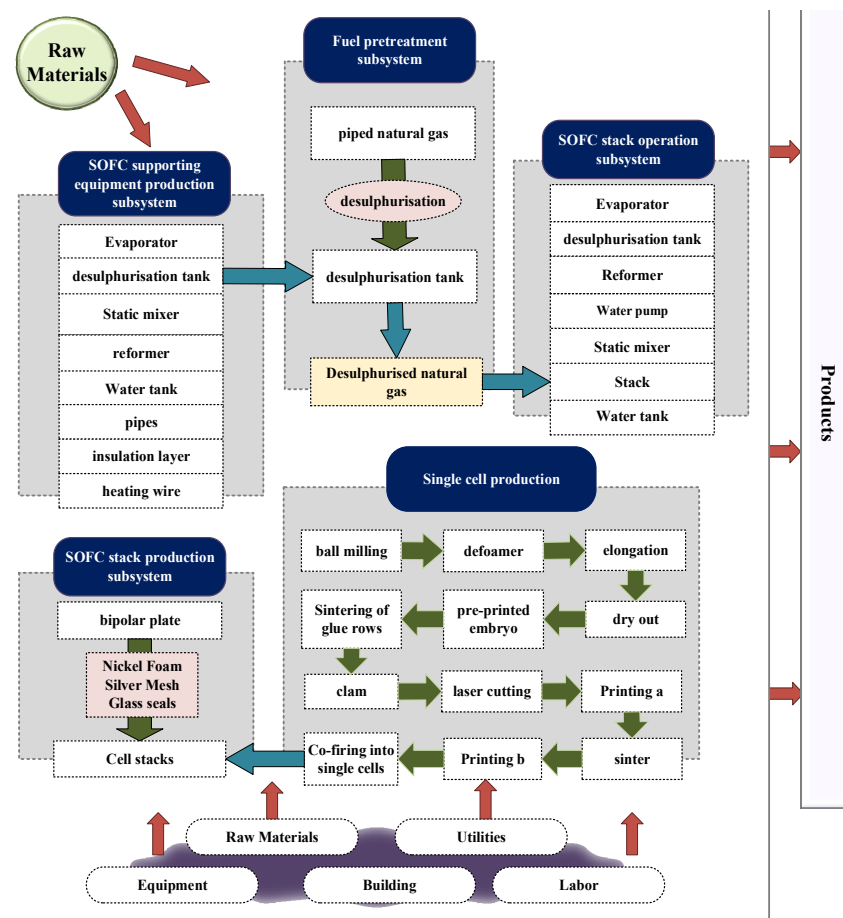


**Figure 2.** Economic flow analysis model of a solid oxide fuel cell system.

### 3.2. Life Cycle Cost Inventory

#### 3.2.1. Relevant Data Collection

The data collection related to promotion is based on the industry benchmark and product production status. Decided by the company's senior leaders, the following provided data can be used for reference.

1. Implementation schedule: the construction period is 3 years.
2. Funding source: the fixed asset investment funding budget is totally CNY 3.3560 million.
3. Depreciation of fixed assets and amortization of intangible and current assets: the depreciation life of fixed assets is 10 years, and the residual value rate is 5.0%; the residual value of intangible and current assets is 0.
4. The industry benchmark return is 10%.
5. The expected selling price of the system is set at around CNY 80,000 per piece.

#### 3.2.2. Cost Estimation

The initial investment cost of the equipment includes the cost of fixed assets, intangible assets, and deferred assets. The operation period is 10 years, with an annual interest rate of 10%, and the depreciation period of fixed assets is also 10 years, with a residual value rate of 5.0%. Table 2 shows the main data of the economic analysis obtained from the calculation. Table 3 shows the annual cost of expenditures after the project is in operation.

**Table 2.** Main cost data.

| Number | Project                               | Value/CNY Million | Operating Period /CNY Million·Year <sup>−1</sup> | Salvage Value /CNY Million |
|--------|---------------------------------------|-------------------|--------------------------------------------------|----------------------------|
| 1      | Fixed assets                          | 335.60            | 54.61                                            | 16.78                      |
| 2      | Intangible assets and deferred assets | 33.56             | 5.46                                             | 0.00                       |
| 3      | Money in circulation                  | 300.00            | 0.00                                             | 0.00                       |
| 4      | Land use cost                         | 30.00             | 0.00                                             | 0.00                       |
|        | Total                                 | 699.16            | 60.07                                            | 16.78                      |

**Table 3.** Annual expenditure.

| Categories             | Cost                                |         | Categories       | Cost                                |           |
|------------------------|-------------------------------------|---------|------------------|-------------------------------------|-----------|
| Natural gas            | CNY million·m <sup>3</sup>          | 0.00037 | Powder j         | CNY million·cylinders <sup>−1</sup> | 0.0087    |
|                        | Year/m <sup>3</sup>                 | 6363.74 |                  | cylinders                           | 88        |
| N <sub>2</sub>         | CNY million·cylinders <sup>−1</sup> | 0.006   | Catalysts        | CNY million·kg <sup>−1</sup>        | 0.06      |
|                        | cylinders                           | 10      |                  | kg                                  | 5         |
| Complementary facility | Material cost/ CNY million          | 110.4   | Purified water   | CNY million·barrel <sup>−1</sup>    | 0.0035    |
|                        | Material cost/ CNY million          | 120.96  |                  | barrel                              | 256       |
| Stack                  | Coating cost/ CNY million           | 178.56  | Print Cutting    | CNY million                         | 178.56    |
|                        |                                     |         |                  |                                     |           |
| Powder a               | CNY million·kg <sup>−1</sup>        | 0.096   | Water            | CNY million·t <sup>−1</sup>         | 0.00022   |
|                        | kg                                  | 21      |                  | t                                   | 821.25    |
| Powder b               | CNY million·kg <sup>−1</sup>        | 0.0735  | Desulphurization | CNY million·kg <sup>−1</sup>        | 0.028     |
|                        | kg                                  | 148     |                  | kg                                  | 3         |
| Powder c               | CNY million·cylinders <sup>−1</sup> | 0.0034  | Reagents g       | CNY million·cylinders <sup>−1</sup> | 0.00144   |
|                        | cylinders                           | 26      |                  | cylinders                           | 6         |
| Powder d               | CNY million·cylinders <sup>−1</sup> | 0.0038  | Powder h         | CNY million·cylinders <sup>−1</sup> | 0.0529    |
|                        | cylinders                           | 13      |                  | cylinders                           | 9         |
| Powder e               | CNY million·kg <sup>−1</sup>        | 0.0105  | Powder i         | CNY million·cylinders <sup>−1</sup> | 0.0015    |
|                        | kg                                  | 51      |                  | cylinders                           | 18        |
| Powder f               | CNY million·barrel <sup>−1</sup>    | 0.012   | Electrical power | CNY million·kWh <sup>−1</sup>       | 0.000056  |
|                        | barrel                              | 10      |                  | kWh                                 | 32,871.48 |
| Total                  | CNY million·Year <sup>−1</sup>      |         |                  |                                     | 609.161   |

Workers' wages and welfare are included in the running cost, and there are 25 permanent employees, 18 operating employees, 4 management employees, and 3 leaders. The per capita salary of personnel is calculated at CNY 5000/month (without overtime working hours), and the per capita salary of management personnel is calculated at CNY 7000/month. Specific estimates are shown in Table 4. The total cost is estimated in Table 5.

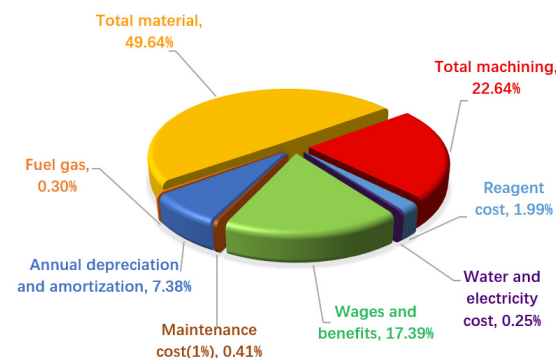
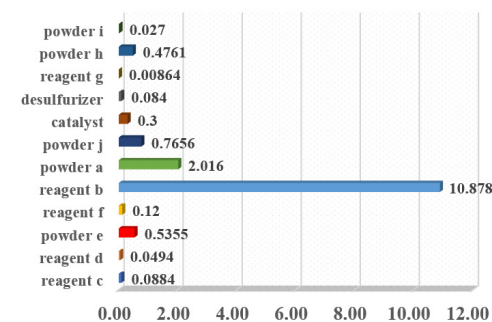
**Table 4.** Personnel wages.

|                                                 | Staff  | Managerial Staff |
|-------------------------------------------------|--------|------------------|
| Number of staff                                 | 18     | 4                |
| Wages/person—(CNY million-month <sup>−1</sup> ) | 0.5    | 0.7              |
| Wages (CNY million-year <sup>−1</sup> )         | 108.0  | 33.6             |
| Total/ CNY million-year <sup>−1</sup>           | 141.60 |                  |

**Table 5.** Total cost expense estimate.

| Number | Project                              | Annual Running Cost/ CNY Million Year <sup>−1</sup> |
|--------|--------------------------------------|-----------------------------------------------------|
| 1      | Annual depreciation and amortization | 60.07                                               |
| 2      | Fuel gas                             | 2.42                                                |
| 3      | Total material                       | 404.16                                              |
| 4      | Total machining                      | 184.32                                              |
| 5      | Reagent cost                         | 16.24                                               |
| 6      | Water and electricity                | 2.02                                                |
| 7      | Wages and benefits                   | 141.60                                              |
| 9      | Maintenance (1%)                     | 3.36                                                |
|        | Total cost                           | 814.19                                              |

As can be seen from Figure 3, the total annual running cost has the largest percentage of total material cost at 49.64%, followed by total processing cost at 22.641%, and workers' welfare and salary cost at 17.39%. Figure 4 shows the cost of reagents required to manufacture 96 systems.

**Figure 3.** Total cost structure.**Figure 4.** Composition of reagent cost.

### 3.2.3. Sales Revenue and Tax Estimation

The revenue of this project comes from the SOFC system. The construction period of this project is 3 years, and the first year is 25% of the total investment, the second year is 50%,

and the third year is 25%. During the second year of construction, the manufacturer can produce 4 power generation systems per month. In the sixth year and after the intelligent production, the manufacturer can steadily produce 800 units, and the price is CNY 80,000. The annual sales revenue and tax estimates are shown in Table A1.

### 3.3. Life Cycle Cost Analysis

#### 3.3.1. Economic Evaluation Indicators

The economic evaluation is in the form of a survey, analysis, and prediction of various relevant technical and economic factors and programme inputs and outputs during the calculation period of the project programme, and uses indicators to calculate and evaluate the economic effects. A comprehensive economic evaluation is conducted by analyzing the financial feasibility and economic feasibility. According to whether to consider the time value of the economy, economic evaluation indicators can be divided into static evaluation indicators and dynamic evaluation indicators. Static evaluation indicators do not consider the time value of money, and the advantage is easy to calculate and easy to understand, but cannot accurately reflect the actual situation of the investment project. Dynamic evaluation indicators consider the time value of money, such as payback period, net present value, internal rate of return, etc., which are more scientific and comprehensive than static evaluation indicators [25].

- Financial NPV

The Financial Net Present Value (NPV) refers to the cumulative value of the present value of the project according to the sector or industry benchmark rate of return or set discount rate. The net cash flow of each year of the calculation period discounted to the year of the starting point of the construction and is one of the important indicators of the dynamic evaluation of the project, as well as being the main examination of the project in the entire calculation period of the distribution of cash flow at the time of the analysis [26–28]. Its expression is:

$$NPV = \sum_{t=1}^n (CI - CO)_t (1 + i_0)^{-t} \quad (1)$$

where  $CI$ —Cash Inflow, CNY million;  $CO$ —Cash Outflow, CNY million;

$(CI - CO)_t$ —Net Cash Flow in year  $t$ , CNY million;

$i_0$ —Baseline Discount Rate, %;  $n$ —typically the life of the project, years.

- Internal rate of return

The internal rate of return, also known as internal rate of return, is the discount rate when the total present value of capital inflows is equal to the total present value of capital flows and the net present value is equal to zero. It is the project's maximum resistance to the risk of the initial investment or the project's maximum rate of currency depreciation that it can withstand. Its expression is:

$$\sum_{t=1}^n (CI - CO)_t (1 + IRR)^{-t} = 0 \quad (2)$$

- Payback period

The payback period refers to the time needed to recover all the investment from the date of project construction, which is an indicator reflecting the investment recovery ability [26]. It can be divided into dynamic payback period and static payback period. Its expression is:

$$\sum_{t=1}^{P_t} (CI - CO)_t = 0 \quad (3)$$

As shown in Table A1, the main operating cost of selling 96 units of a power generation system is CNY 7,541,900, the annual sales revenue is CNY 7,680,000, and the administrative expenses are CNY 30,720,000 (overhead rate of 0.4%), selling expenses are CNY 15,360,000 (selling rate of 0.2%), and taxes are CNY 384,000 (after sales tax is 5%). Calculated by the

investment cash flow of the IRR of 32.02%, the financial NPV ( $i_0 = 10\%$ ) is CNY 19,763,300, static Pt is 5.544 years (including the construction period), dynamic Pt is 6.179 years (including the construction period), the profitability is better, the Pt is shorter, and the IRR is greater than the industry benchmark rate of return.

### 3.3.2. Economic Benefits Impact Factor Analysis

This paper selects system material costs, total processing costs (including coating costs and cutting costs), other raw material costs (reagent costs and fuel costs, etc.), construction investment costs, sales prices, wages, and benefits as the influencing factors. Raw materials, materials, and processing costs are shown in Figure 5.

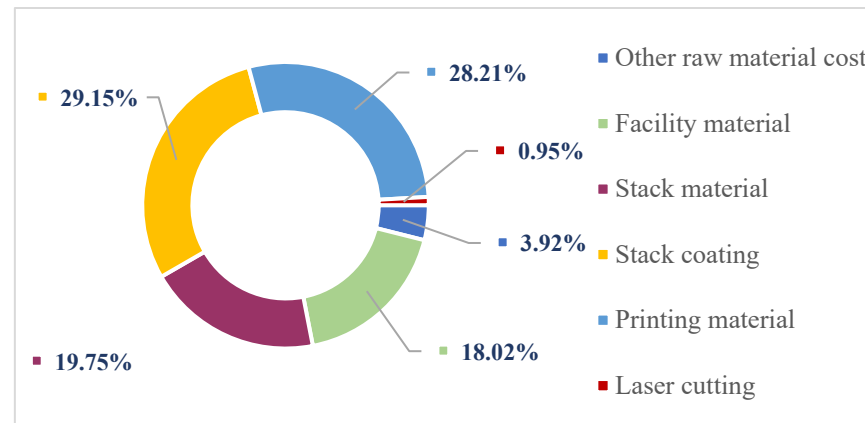


Figure 5. Raw materials and processing cost structure.

Figure 6 shows the break-even analysis. When the annual production and sales need to reach 19.38% of the design capacity, the goal of break-even can be achieved.

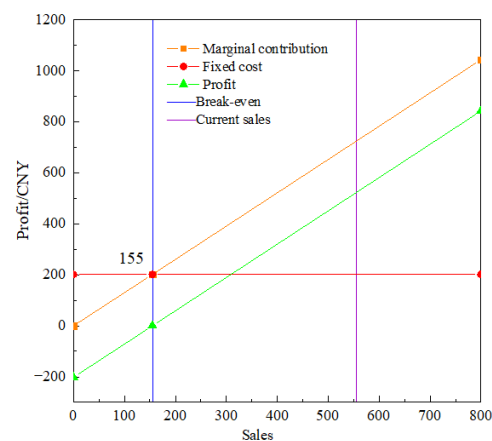


Figure 6. Break-even analysis.

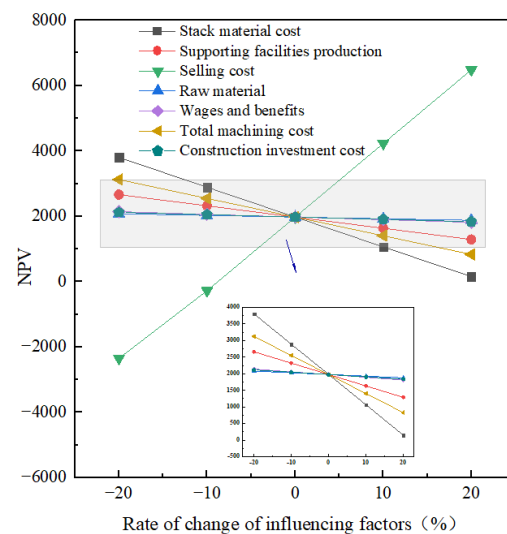
### 3.3.3. Economic Sensitivity Analysis

The sensitivity analysis of the NPV is presented in the Table 6.

As can be seen from Figure 7, when the sales price increases, the financial NPV shows a linear growth trend. When the stacking material cost, auxiliary facility material cost, total processing cost, wages and benefits, raw material cost, and construction investment cost increase, the financial NPV shows a decreasing trend. The biggest influence on the NPV among the influencing factors is the sales price: when the sales price decreases by 10%, the financial NPV decreases from CNY 19,763,300 to CNY −2,769,900. This is followed by the stack material cost: when the influencing factor increases from −20% to 20%, the financial NPV decreases from CNY 38,023,000 to CNY 1,503,600.

**Table 6.** Sensitivity analysis of the NPV of each factor.

| Rate of Change                 | −20%     | −10%     | 0       | 10%      | 20%      |
|--------------------------------|----------|----------|---------|----------|----------|
| Stack Materials                | 0.0408   | 0.0459   | 0.051   | 0.0561   | 0.0612   |
| The changed material costs     | 345.408  | 374.784  | 404.16  | 433.536  | 462.912  |
| The changed business costs     | 695.367  | 724.743  | 754.119 | 783.495  | 812.871  |
| NPV/CNY                        | 3802.30  | 2889.31  | 1976.33 | 1063.34  | 150.36   |
| The changed material costs     | 323.328  | 363.744  | 404.16  | 444.576  | 484.992  |
| The changed business costs     | 732.039  | 743.079  | 754.119 | 765.159  | 776.199  |
| NPV/CNY                        | 2662.56  | 2319.44  | 1976.33 | 1633.21  | 1290.10  |
| The changed Sales profits      | 6.4      | 7.2      | 8       | 8.8      | 9.6      |
| NPV/CNY                        | -        | −276.90  | 1976.33 | 4229.50  | 6482.78  |
| The changed wages              | 113.28   | 127.44   | 141.6   | 155.76   | 169.92   |
| The changed business cost      | 755.999  | 770.159  | 784.319 | 798.479  | 812.639  |
| NPV/CNY                        | 2140.35  | 2058.34  | 1976.33 | 1894.32  | 1812.31  |
| The changed processing cost    | 147.456  | 165.888  | 184.32  | 202.752  | 221.184  |
| The changed business cost      | 688.503  | 736.311  | 784.319 | 831.927  | 879.735  |
| NPV/CNY                        | 3122.04  | 2549.18  | 1976.33 | 1403.47  | 830.62   |
| The changed raw material cost  | 12.9952  | 14.6196  | 16.244  | 17.8684  | 19.4928  |
| The changed business cost      | 750.8702 | 752.4946 | 754.119 | 755.7434 | 757.3678 |
| NPV/CNY                        | 2077.30  | 2026.81  | 1976.33 | 1925.84  | 1875.36  |
| The changed initial investment | 559.328  | 629.244  | 699.16  | 769.076  | 838.992  |
| NPV/CNY                        | 2116.16  | 2046.24  | 1976.33 | 1906.41  | 1836.50  |

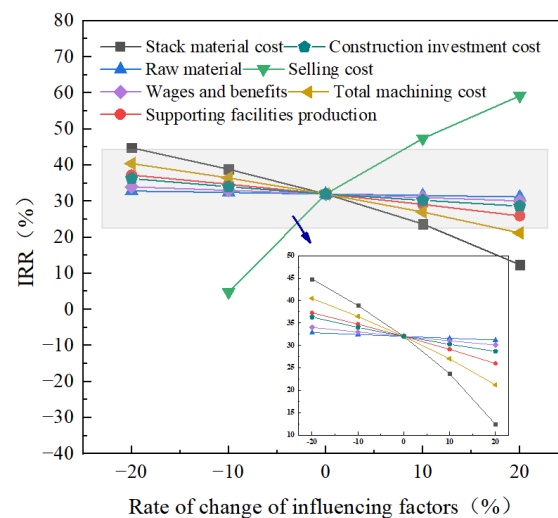
**Figure 7.** Relationship between the financial NPV and influencing factors.

The sensitivity analysis of the IRR is presented in Table 7.

As can be seen from Figure 8, similar to the change rule of the financial NPV, the IRR is affected by factors with a wide range of changes in the sales price. When the sales price decreases by 10%, the IRR decreases from 32.02% to 4.78%; when the cost of stack materials increases from −10% to 10%, the IRR decreases from 38.87% to 23.70%; when ancillary facilities materials costs, wages and benefits, raw material costs, and total machining costs increase, the IRR return falls slightly.

**Table 7.** Sensitivity analysis of the IRR of each factor.

| Rate of Change                 | −20%     | −10%     | 0       | 10%      | 20%      |
|--------------------------------|----------|----------|---------|----------|----------|
| Stack Materials                | 0.0408   | 0.0459   | 0.051   | 0.0561   | 0.0612   |
| The changed material costs     | 345.408  | 374.784  | 404.16  | 433.536  | 462.912  |
| The changed business costs     | 695.367  | 724.743  | 754.119 | 783.495  | 812.871  |
| IRR                            | 44.81%   | 38.87%   | 32.02%  | 23.70%   | 12.41%   |
| The changed material costs     | 323.328  | 363.744  | 404.16  | 444.576  | 484.992  |
| The changed business costs     | 732.039  | 743.079  | 754.119 | 765.159  | 776.199  |
| IRR                            | 37.27%   | 34.73%   | 32.02%  | 29.12%   | 25.96%   |
| The changed Sales profits      | 6.4      | 7.2      | 8       | 8.8      | 9.6      |
| IRR                            | -        | 4.78%    | 32.02%  | 47.37%   | 59.21%   |
| The changed wages              | 113.28   | 127.44   | 141.6   | 155.76   | 169.92   |
| The changed business cost      | 755.999  | 770.159  | 784.319 | 798.479  | 812.639  |
| IRR                            | 33.99%   | 33.00%   | 32.02%  | 31.05%   | 30.09%   |
| The changed processing cost    | 147.456  | 165.888  | 184.32  | 202.752  | 221.184  |
| The changed business cost      | 688.503  | 736.311  | 784.319 | 831.927  | 879.735  |
| IRR                            | 40.46%   | 36.45%   | 32.02%  | 27.03%   | 21.21%   |
| The changed raw material cost  | 12.9952  | 14.6196  | 16.244  | 17.8684  | 19.4928  |
| The changed business cost      | 750.8702 | 752.4946 | 754.119 | 755.7434 | 757.3678 |
| IRR                            | 32.84%   | 32.43%   | 32.02%  | 31.61%   | 31.19%   |
| The changed initial investment | 559.328  | 629.244  | 699.16  | 769.076  | 838.992  |
| IRR                            | 36.31%   | 34.02%   | 32.02%  | 30.25%   | 28.66%   |

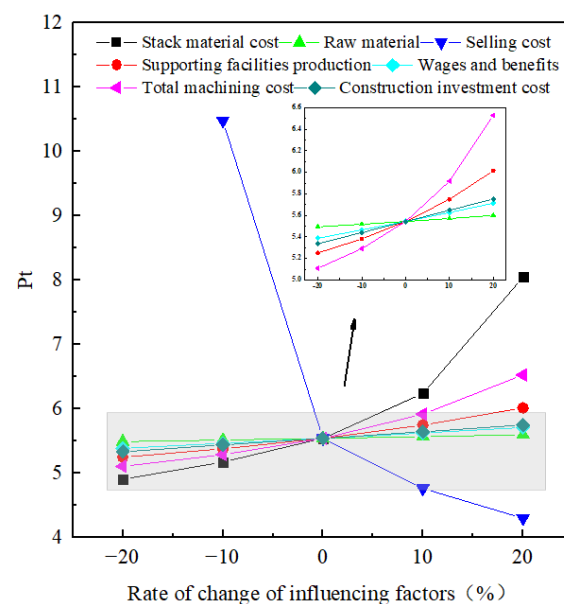
**Figure 8.** Relationship between the financial IRR and influencing factors.

The sensitivity analysis of  $P_t$  is presented in Table 8.

As can be seen from Figure 9, the  $P_t$  decreases when the selling price increases, and the  $P_t$  increases when the stack material cost increases. The  $P_t$  increases slowly when the remaining ancillary facility material costs, raw material costs, wage and benefit costs, total processing costs, and construction investment cost variables increase, while it increases significantly when the sales price decreases by 10%, indicating that it will be in the red for a long period of time if the sales pricing decreases by −10%.

**Table 8.** Sensitivity analysis of  $P_t$  of each factor.

| Rate of Change                 | −20%     | −10%     | 0       | 10%      | 20%      |
|--------------------------------|----------|----------|---------|----------|----------|
| Stack Materials                | 0.0408   | 0.0459   | 0.051   | 0.0561   | 0.0612   |
| The changed material costs     | 345.408  | 374.784  | 404.16  | 433.536  | 462.912  |
| The changed business costs     | 695.367  | 724.743  | 754.119 | 783.495  | 812.871  |
| $P_t$                          | 4.907    | 5.176    | 5.544   | 6.239    | 8.046    |
| The changed material costs     | 323.328  | 363.744  | 404.16  | 444.576  | 484.992  |
| The changed business costs     | 732.039  | 743.079  | 754.119 | 765.159  | 776.199  |
| $P_t$                          | 5.250    | 5.382    | 5.544   | 5.749    | 6.015    |
| The changed Sales profits      | 6.4      | 7.2      | 8       | 8.8      | 9.6      |
| $P_t$                          | -        | 10.478   | 5.544   | 4.766    | 4.302    |
| The changed wages              | 113.28   | 127.44   | 141.6   | 155.76   | 169.92   |
| The changed business cost      | 755.999  | 770.159  | 784.319 | 798.479  | 812.639  |
| $P_t$                          | 5.388    | 5.465    | 5.544   | 5.626    | 5.712    |
| The changed processing cost    | 147.456  | 165.888  | 184.32  | 202.752  | 221.184  |
| The changed business cost      | 688.503  | 736.311  | 784.319 | 831.927  | 879.735  |
| $P_t$                          | 5.108    | 5.291    | 5.544   | 5.918    | 6.528    |
| The changed raw material cost  | 12.9952  | 14.6196  | 16.244  | 17.8684  | 19.4928  |
| The changed business cost      | 750.8702 | 752.4946 | 754.119 | 755.7434 | 757.3678 |
| $P_t$                          | 5.493    | 5.518    | 5.544   | 5.571    | 5.599    |
| The changed initial investment | 559.328  | 629.244  | 699.16  | 769.076  | 838.992  |
| $P_t$                          | 5.337    | 5.441    | 5.544   | 5.647    | 5.751    |

**Figure 9.** Relationship between the financial  $P_t$  and influencing factors.

From the previous study, it is known that the whole life cycle greenhouse gas emissions of the 2 kW SOFC power generation system are converted to 5592 kg of  $\text{CO}_2$  [13], and the whole life cycle greenhouse gas emissions of the same power thermal power generation system [29] are converted to 8638 kg of  $\text{CO}_2$ . If the thermal power generation system is replaced by this SOFC power generation system, it can reduce  $\text{CO}_2$  by 6670.74 kg/y. The pilot policy of China's carbon trading market has a positive impact on the enterprise's green innovation [30], and the trading price of the carbon market in the Jiangsu and Zhejiang provinces is generally 50~70 CNY/t [31]. Based on the above economic analysis model, assuming the thermal power generation's  $\text{CO}_2$  emissions for the project's original carbon credits, the daily trading price is taken as a 10% rate of change and the other values remain

unchanged (Table A2), then the impact of the changed results on the project's financial NPV and IRR is shown in Figure 10.

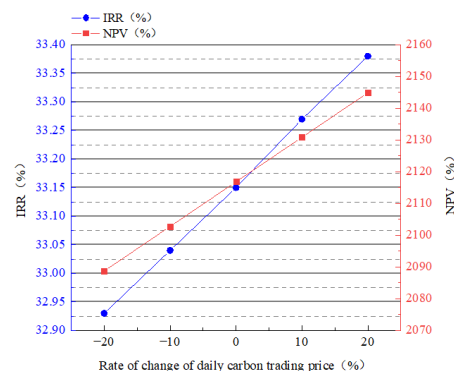


**Figure 10.** Effect of the daily carbon trading price on the financial NPV and IRR.

As can be seen from Figure 10, the daily carbon trading price changes in the financial NPV and IRR impact are consistent, and the higher the daily carbon trading price, the higher the financial NPV and IRR. In the low carbon context, promoting SOFC systems has economic potential compared to traditional energy generation modes.

#### 4. Conclusions

This paper presents an economic analysis of the 2 kW SOFC system by modelling the economic flow analysis. With respect to previous research, this paper expands the economic analysis of the life cycle of low-power household SOFC systems, and makes it easier for enterprises to adjust the cost structure by evaluating the cost at each stage of the product. On the basis of comprehensive economic indicators such as the NPV, Pt, and IRR, an economic analysis of carbon market trading is conducted compared with traditional power generation systems, and the economic potential of SOFC systems for market promotion is evaluated based on case data. The results show that the construction period of the project is 3 years, the operating life is 10 years, the depreciation life of fixed assets is 10 years, the annual rate of return is about 10%, and the total material cost accounts for the largest proportion of 49.64%, followed by the total processing cost of 22.641%. Workers' welfare and salary costs accounted for 17.39%, and when the annual production and sales need to reach 19.38% of the design capacity, the goal of break-even can be achieved. Changes in the daily carbon trading price have a consistent impact on the financial NPV and IRR. The higher the daily carbon trading price, the higher the financial NPV and IRR increase, and in the low carbon context, compared with the traditional energy generation model, promoting SOFC systems seems to have a good economic potential and prospects for large-scale commercialization and expansion.

**Supplementary Materials:** The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/en17112694/s1>.

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## Appendix A

Table A1. Economic index of system sales.

| Project                            | 1st            | 2nd      | 3rd     | 4th     | 5th     | 6th     | 7th     | 8th     | 9th      | 10th      | 11th      | 12th     | 13th      |
|------------------------------------|----------------|----------|---------|---------|---------|---------|---------|---------|----------|-----------|-----------|----------|-----------|
| Sales Volume                       | 0              | 48       | 96      | 192     | 480     | 800     | 800     | 800     | 800      | 800       | 800       | 800      | 800       |
| Annual Sales revenue               | 0              | 384      | 768     | 1536    | 3840    | 6400    | 6400    | 6400    | 6400     | 6400      | 6400      | 6400     | 6400      |
| Taxes and surcharges               | 0              | 19.2     | 38.4    | 76.8    | 192     | 320     | 320     | 320     | 320      | 320       | 320       | 320      | 320       |
| Main business cost                 | 0              | 447.8595 | 754.119 | 1366.64 | 3204.2  | 5245.93 | 5246.59 | 5245.93 | 5245.925 | 5245.925  | 5245.925  | 5245.925 | 5245.925  |
| Sales profit                       | 0              | -83.0595 | -24.519 | 92.562  | 443.805 | 834.075 | 833.408 | 834.075 | 834.075  | 834.075   | 834.075   | 834.075  | 834.075   |
| overhead                           | 0              | 1.536    | 3.072   | 6.144   | 15.36   | 25.6    | 25.6    | 25.6    | 25.6     | 25.6      | 25.6      | 25.6     | 25.6      |
| Selling expenses                   | 0              | 0.768    | 1.536   | 3.072   | 7.68    | 12.8    | 12.8    | 12.8    | 12.8     | 12.8      | 12.8      | 12.8     | 12.8      |
| Total profit                       | 0              | -85.3635 | -29.127 | 83.346  | 420.765 | 795.675 | 795.008 | 795.675 | 795.675  | 795.675   | 795.675   | 795.675  | 795.675   |
| Income tax                         | 0              | -12.8045 | -4.3691 | 12.5019 | 63.1148 | 119.351 | 119.251 | 119.351 | 119.3513 | 119.35125 | 119.35125 | 119.3513 | 119.35125 |
| Net profit                         | 0              | -72.559  | -24.758 | 70.8441 | 357.65  | 676.324 | 675.757 | 676.324 | 676.3238 | 676.32375 | 676.32375 | 676.3238 | 676.32375 |
|                                    | 1              | 2        | 3       | 4       | 5       | 6       | 7       | 8       | 9        | 10        | 11        | 12       | 13        |
| Net cash flow                      | -699.16        | -72.559  | -24.758 | 70.8441 | 357.65  | 676.324 | 675.757 | 676.324 | 676.3238 | 676.32375 | 676.32375 | 676.3238 | 676.32375 |
| Accumulated net cash flow          | -699.16        | -771.719 | -796.48 | -725.63 | -367.98 | 308.341 | 984.098 | 1660.42 | 2336.746 | 3013.0695 | 3689.3933 | 4365.717 | 5042.0408 |
| IRR                                | 32.02%         |          |         |         |         |         |         |         |          |           |           |          |           |
| Pt                                 | 5.544092       |          |         |         |         |         |         |         |          |           |           |          |           |
| NPV                                | CNY<br>1976.01 |          |         |         |         |         |         |         |          |           |           |          |           |
|                                    | 1              | 2        | 3       | 4       | 5       | 6       | 7       | 8       | 9        | 10        | 11        | 12       | 13        |
| Discounted net cash flow           | -699.16        | -65.9627 | -20.461 | 53.2262 | 244.28  | 419.944 | 381.447 | 347.061 | 315.51   | 286.82729 | 260.75208 | 237.0473 | 215.49759 |
| Accumulated net cash flow discount | -699.16        | -765.123 | -785.58 | -732.36 | -488.08 | -68.134 | 313.313 | 660.374 | 975.8845 | 1262.7118 | 1523.4638 | 1760.511 | 1976.0088 |
| Dynamic Pt                         | 6.178619       |          |         |         |         |         |         |         |          |           |           |          |           |

**Table A2.** Economic index of system sales after carbon market trading.

[illegible]

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