

## Article

# Kinetic Modeling and Optimization of a Low-Carbon Tri-Generation System Based on Calcium-Looping, Sorption-Enhanced Steam Methane Reforming

Jiale Li <sup>1</sup>, Linbo Yan <sup>1,\*</sup>, Liang Wang <sup>1,2</sup>, Shishu Qi <sup>1</sup>, Yuhan Duan <sup>1</sup>, Zhenning Feng <sup>1</sup>, Zhiquan Ren <sup>1</sup>, Siyu Chen <sup>2</sup> and Ziyue Jia <sup>2</sup>

<sup>1</sup> Institute of Combustion and Thermal System, School of Mechanical, Electronic and Control Engineering, Beijing Jiaotong University, Beijing 100044, China

<sup>2</sup> Nuclear Industry Engineering Research and Design Co., Ltd., Beijing 101300, China

\* Correspondence: lbyan@bjtu.edu.cn

## Abstract

Combined cooling, heating, and power (CCHP) tri-generation systems can greatly improve comprehensive energy utilization efficiency thanks to their energy-cascade utilization concept. However, traditional fossil-fuel-based CCHP systems still suffer from intensive carbon emissions, hindering their further development in the current low-carbon scenario. To solve this issue, a new low-carbon CCHP system (LC-CCHP) integrating a calcium-looping, sorption-enhanced steam methane reforming (CL-SE-SMR) unit, a lithium bromide absorption chiller, and a hydrogen gas turbine is proposed in this work, and the corresponding system model is built to evaluate its performance. The proposed system features an innovative architecture that integrates carbon capture directly into the reforming process, which simultaneously enables a high hydrogen yield and low carbon-capture penalty. Moreover, instead of the widely used thermodynamic equilibrium assumption, a detailed kinetic model is employed for the CL-SE-SMR unit, which provides more realistic predictions and greater reference value for practical engineering applications. Then, multi-objective optimization is conducted using a particle swarm optimization algorithm to identify the optimal operating conditions. It is found that the proposed system performs best at a steam-to-carbon molar ratio of 4.37, a calcium-to-carbon mass ratio of 6.23, an air-equivalency molar ratio of 1.39 for a hydrogen gas turbine and a reaction temperature of 600 °C for SE-SMR. Under these operating conditions, the system can achieve a carbon-capture rate of 89.2%, an exergy efficiency of 45.7%, an energy efficiency of 95.4%, and a levelized cost of exergy of 0.109 \$/kWh.

**Keywords:** combined cooling heating and power system; calcium-looping, sorption-enhanced steam methane reforming; kinetic model; multi-objective optimization

Academic Editor: Marco Martino

Received: 18 June 2026

Revised: 21 July 2026

Accepted: 27 July 2026

Published: 29 July 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

## 1. Introduction

The rapid development of human society has led to a continuous rise in fossil fuel consumption **Error! Reference source not found.** However, excessive reliance on fossil fuel leads to the dual issues of energy shortage and global warming **Error! Reference source not found.** In this scenario, various combined cooling, heating and power (CCHP) systems have been proposed as potential solutions **Error! Reference source not found.**

Lu et al. **Error! Reference source not found.** proposed a methane-fueled marine CCHP system that combines a solid oxide fuel cell (SOFC), a gas turbine (GT) and a three-effect lithium bromide refrigeration machine. The system can achieve an energy efficiency of 75.4% and an exergy efficiency of 55.2%. Khalvan et al. **Error! Reference source not found.** proposed a natural-gas-based CCHP system consisting of a GT, a modified compression refrigeration cycle, and a renewable-integrated energy storage unit. The system achieved a total energy efficiency of 65.98% and a power generation efficiency of 54.06%. Chahartaghi et al. **Error! Reference source not found.** presented a natural-gas-based CCHP system with a steam boiler, a steam turbine, a heat exchanger, and a single-effect absorption chiller, which attained an energy efficiency of 94.51%.

Although conventional fossil-fuel-based CCHP systems can attain high energy efficiency and can thereby reduce carbon emissions to some extent, carbon emissions are still intensive because no carbon-capture technology is used **Error! Reference source not found.** To address this issue, numerous studies have focused on reducing the carbon emissions of CCHP systems. Hai et al. **Error! Reference source not found.** used temperature-swing adsorption (TSA) technology to separate CO<sub>2</sub> from flue gas in a CCHP system, which significantly reduced the system's net CO<sub>2</sub> emissions from 0.9183 kg/s to 0.41 kg/s. However, the physical TSA process requires heating of the adsorbent to 80–120 °C for desorption, which results in a high energy penalty. In addition, it is reported that the exergy efficiency of TSA is low, ranging from 3.24% to 9.23% **Error! Reference source not found.** Akbarnataj et al. **Error! Reference source not found.** integrated a novel cryogenic carbon-capture unit (CCU) into a CCHP system, which reduced CO<sub>2</sub> emissions by up to 91% while increasing auxiliary energy consumption by 41.17 kW. Furthermore, researchers adopted a membrane-based CCU to replace a cryogenic CCU **Error! Reference source not found.**, achieving an exergy efficiency of 44.96% and a reduction in carbon emission intensity from 0.036 kg/kWh to 0.027 kg/kWh. However, the total cost increased by 1.83 \$/h compared with the cryogenic CCU-based CCHP system.

However, the above-mentioned improvements to CCHP systems still suffer from a fundamental trade-off. Achieving a high carbon-capture rate generally causes substantial energy penalties, which undermine the overall system economics. To overcome this limitation, the integration of calcium-looping, sorption-enhanced steam methane reforming (CL-SE-SMR) offers a promising alternative, which is one major novelty of this work. This technology combines in situ CO<sub>2</sub> capture with calcium-looping heat supply, enabling high methane conversion and carbon-capture efficiency without excessive energy consumption. In the CL-SE-SMR process, CaO captures CO<sub>2</sub> in the produced syngas, releases chemical energy in the form of carbonation, and subsequently promotes H<sub>2</sub> generation due to the shift in chemical equilibrium. CaO can be further regenerated by CaCO<sub>3</sub> calcination, and the absorbed heat can be stored chemically **Error! Reference source not found.** The in situ storage and release of chemical energy during the calcination and carbonation processes happen in an internally connected dual-fluidized bed reactor, leading to little energy being lost during the carbon-capture process. Based on this, a new natural-gas-fueled low-carbon CCHP (LC-CCHP) system is proposed in this work. The proposed LC-CCHP system consists of a CL-SE-SMR unit, a lithium bromide absorption chiller, and a hydrogen gas turbine. To better understand the properties of the LC-CCHP system, it is imperative to systematically investigate its operational performance under various operating conditions. Because the LC-CCHP system is complex, coupling a fossil fuel reactor, refrigeration unit, and power generation unit, the process simulation methodology is adopted before lab-scale and pilot-scale experiments can be implemented **Error! Reference source not found.** Currently, process simulations of the CL-SE-SMR process are mostly performed based on thermodynamic equilibrium assumptions. Yari et al. **Error! Reference source not found.** built a multi-generation system integrating nuclear energy, CL-SE-

SMR, and triple-cycle power generation via Aspen Plus, in which the CL-SE-SMR module was assumed to reach thermodynamic equilibrium. Zare et al. **Error! Reference source not found.** developed a coupled multi-generation system that combines CL-SE-SMR, biogas-fueled chemical-looping combustion, and phosphoric acid fuel cells. Similarly, the CL-SE-SMR process reported in their work was simulated using the thermodynamic equilibrium model. Huang et al. **Error! Reference source not found.** also proposed a solar-assisted CL-SE-SMR hydrogen production system coupled with a SOFC-GT unit, where the CL-SE-SMR process was also modeled using the thermodynamic equilibrium approach.

As is known, the thermodynamic equilibrium method is unable to predict the CL-SE-SMR progress as a function of residence time, sorbent loading and catalyst dosage. Therefore, the simulation results have limited reference value for practical applications. To address the limitations of the thermodynamic equilibrium assumption, a detailed kinetic model for the CL-SE-SMR unit is established and used in the proposed system model, which is also the major novelty of this work. This novelty is particularly important for system-level CCHP design, as the reforming kinetics directly determine the fuel supply to the hydrogen turbine and the heat input to the absorption chiller. With the kinetic model, the proposed LC-CCHP system can be evaluated under realistic design conditions, and the simulation results can provide meaningful guidance for reactor sizing, catalyst inventory selection, and downstream equipment specification.

In this work, the proposed LC-CCHP system is simulated using the developed kinetic model for the CL-SE-SMR unit, and the overall system performance is evaluated from both thermodynamic and economic perspectives. Multi-objective optimization using a particle swarm optimization algorithm is then conducted to identify the optimal operating conditions. The results provide not only a comprehensive performance assessment but also practical insights into the design and operation of the LC-CCHP system.

## 2. Results and Discussion

In this section, the established models are first validated. Then, an orthogonal experiment-based statistical analysis and the multi-objective optimization of the LC-CCHP system are presented.

### 2.1. Modeling Validation

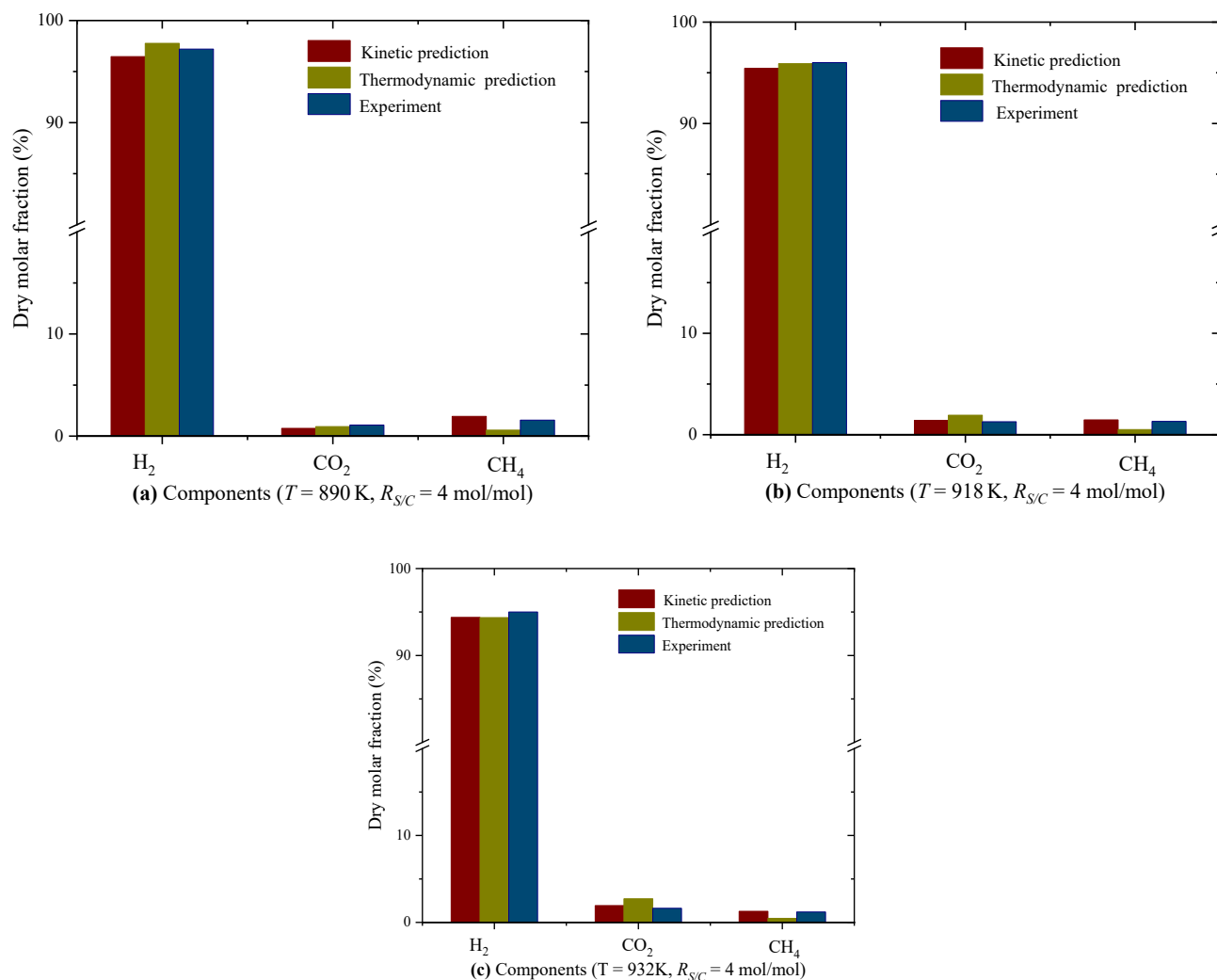
Before the model can be used for prediction and analysis, it first needs to be validated. For the CL-SE-SMR model, both the thermodynamic model and the kinetic model are implemented and the results are compared with experimental data [17]. The chosen operational parameters are summarized in Table 1.

**Table 1.** Main experimental parameters [17]

| Parameter                             | Value   |
|---------------------------------------|---------|
| Static bed height (cm)                | 20      |
| Bed diameter (cm)                     | 8       |
| Total bed material (cm <sup>3</sup> ) | 1004.8  |
| Catalyst particle size (μm)           | 180–425 |
| Dolomite particle size (μm)           | 180–425 |
| Dol/cat ratio vol (-)                 | 4       |

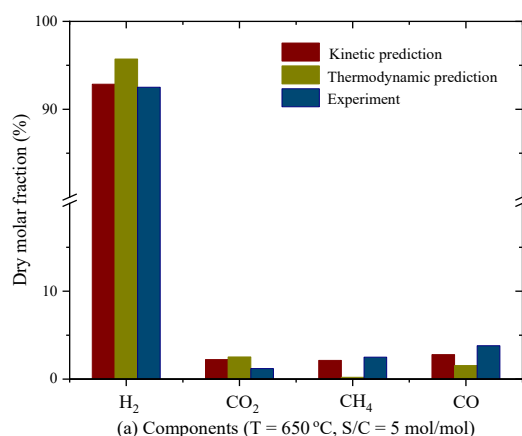
In Figure 1, it can be seen that the relative errors between the kinetic predictions and experimental data for hydrogen at temperatures of 890 K, 918 K, and 932 K are 0.80%, 0.60%, and 0.70%, respectively, indicating that the kinetic model predictions agree well

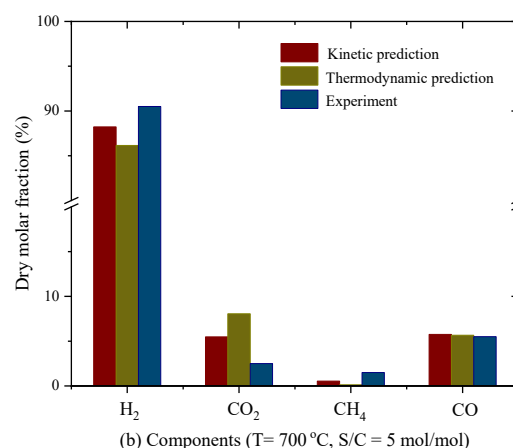
with the experimental data at different temperatures. Compared with the thermodynamic model, the kinetic predictions are more accurate for CH<sub>4</sub> and CO.



**Figure 1.** Comparison of kinetic and thermodynamic predictions against experimental data [17,18].

Another comparison of the kinetic and thermodynamic model predictions with experimental data **Error! Reference source not found.** is shown in Figure 2. The comparison is performed at reaction temperatures of 650 °C and 700 °C and a H<sub>2</sub>O/C molar ratio of 5.0. It can be seen that the kinetic model exhibits significantly higher accuracy in predicting the syngas species fractions compared with the thermodynamic model.





**Figure 2.** Comparison of kinetic and thermodynamic predictions against experimental data **Error! Reference source not found..**

Table 2 compares the results predicted from the lithium bromide absorption refrigeration unit with the data reported in Refs. [20,21]. It can be seen that the maximum deviation is 3.24%.

**Table 2.** Comparison between the refrigeration model predictions and design values.

| Parameter                  | Literature Data | Simulation Result | Deviation % |
|----------------------------|-----------------|-------------------|-------------|
| GENHP load (kW)            | 265.4           | 266               | −0.23       |
| GENHP-to-GENLP energy (kW) | 201.9           | 199.5             | 1.19        |
| Condenser load (kW)        | 183.6           | 180.7             | 1.58        |
| Absorber load (kW)         | 442.5           | 435.2             | 1.65        |
| Evaporator load (kW)       | 360.6           | 349.8             | 2.99        |
| COP                        | 1.359           | 1.315             | 3.24        |

Table 3 compares the results predicted by the hydrogen gas turbine unit with the data reported in Refs. [22,23]. The maximum deviation is 2.60%.

**Table 3.** Comparison between the model predictions and design values [22,23].

| Parameter                              | Design Value | Model Prediction | Deviation % |
|----------------------------------------|--------------|------------------|-------------|
| Compressor pressure ratio              | 17           | 17               | -           |
| Turbine pressure ratio                 | 17           | 17               | -           |
| Net power (MW)                         | 270          | 274.5            | 1.70        |
| Inlet temperature of gas turbine (°C)  | 1400         | 1409.5           | 0.70        |
| Outlet temperature of gas turbine (°C) | 586          | 571.0            | −2.60       |
| Air flow rate (kg/s)                   | 651          | 649.5            | 0.20        |
| Net efficiency (%)                     | 38.2         | 38.5             | 0.80        |

To ensure the reliability and accuracy of the economic methodology, in Table 4, the economic predictions of the main components are compared with the data reported in **Error! Reference source not found..** According to the comparison results, the largest difference lies in the calciner (4.90%). The differences for the remaining components are within 5%.

**Table 4.** Economic validation of main components.

| Component | Unit | Literature Data | Economic Data | Deviation % | Source |
|-----------|------|-----------------|---------------|-------------|--------|
|-----------|------|-----------------|---------------|-------------|--------|

|             |         |       |       |       |                                                                               |
|-------------|---------|-------|-------|-------|-------------------------------------------------------------------------------|
| Reformer    | \$/kmol | 0.172 | 0.164 | −4.70 | Error! Reference source not found. Error! Reference source not found. [26,27] |
| Calciner    | \$/t    | 1.663 | 1.585 | 4.90  |                                                                               |
| Gas turbine | \$/h    | 3.527 | 3.624 | 2.80  |                                                                               |

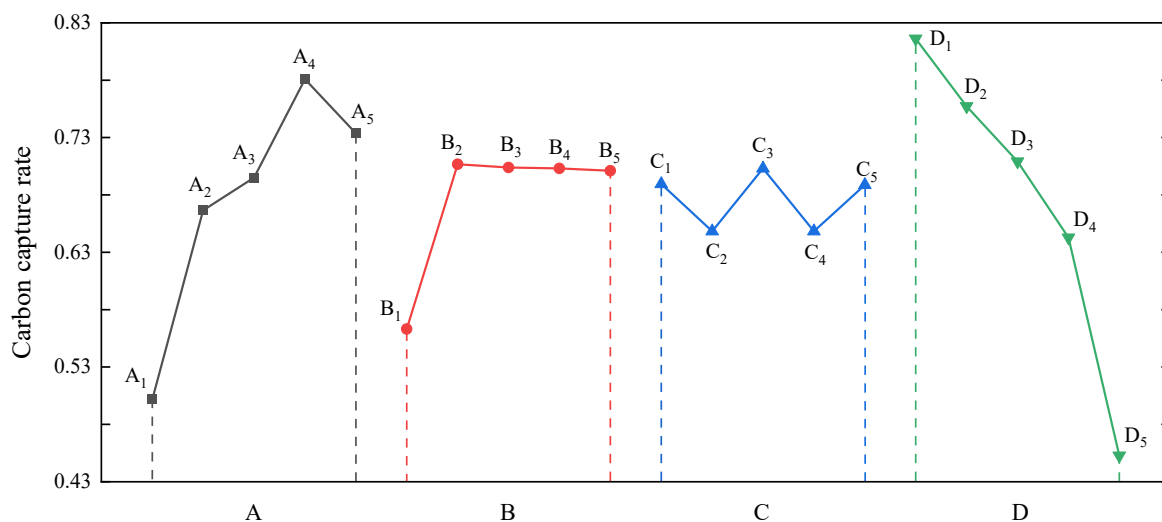
## 2.2. Orthogonal Experimental Analysis

To investigate the comprehensive influence of the optimization variables on the optimization objective, an  $L_{25}(5^6)$  orthogonal array is employed. All 25 simulations are performed using Aspen Plus. The selection of factor levels is shown in Table 5. In orthogonal experimental designs, when all columns are occupied by main effects and interactions, the number of residual degrees of freedom is zero, which renders the error variance inestimable. Hence, several blank columns should be reserved at the design stage to facilitate the estimation of random error.

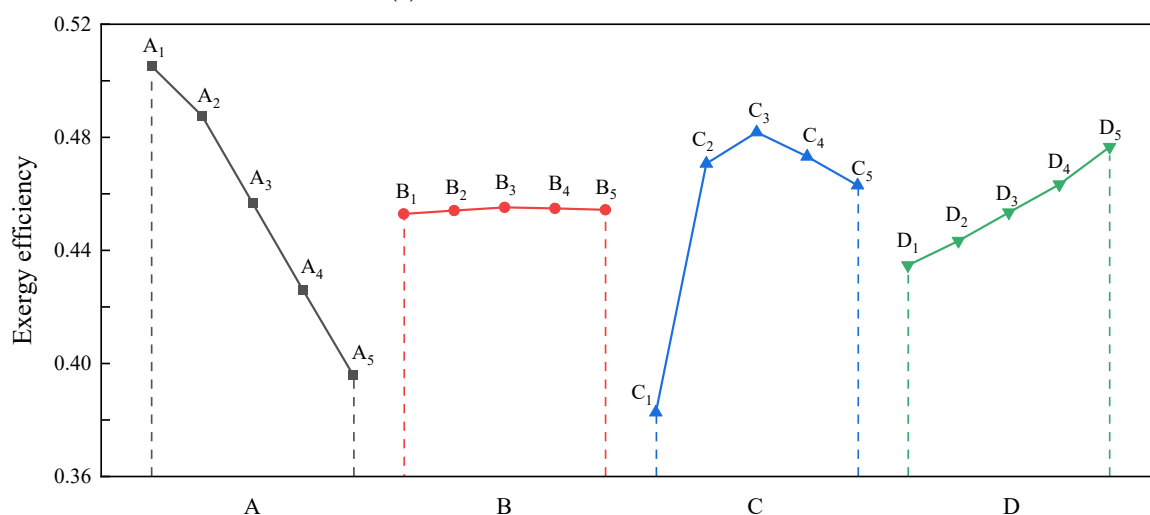
**Table 5.** The six factors and five levels of the orthogonal experiment.

| Factor | $R_{SC}(A)$ | $R_{CC}(B)$ | $R_{AE}(C)$ | $T_{Ref}(D)$ | Empty(E) | Empty(F) |
|--------|-------------|-------------|-------------|--------------|----------|----------|
| Number | A1          | B1          | C1          | D1           | E1       | F1       |
|        | A2          | B2          | C2          | D2           | E2       | F2       |
|        | A3          | B3          | C3          | D3           | E3       | F3       |
|        | A4          | B4          | C4          | D4           | E4       | F4       |
|        | A5          | B5          | C5          | D5           | E5       | F5       |
| Level  | 2           | 2           | 1           | 600          | 1        | 1        |
|        | 3           | 4.5         | 1.2         | 625          | 2        | 2        |
|        | 4           | 7           | 1.4         | 650          | 3        | 3        |
|        | 5           | 9.5         | 1.6         | 675          | 4        | 4        |
|        | 6           | 12          | 1.8         | 700          | 5        | 5        |

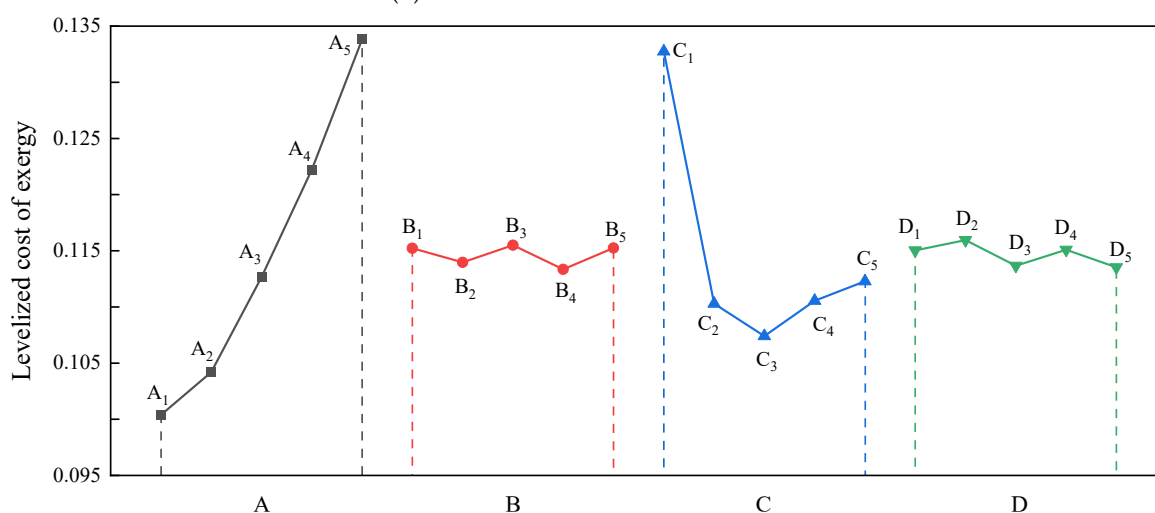
Figure 3 illustrates the variation trends of performance indicators with each factor level. According to the range analysis, the order of the six operating parameters affecting CCR is  $D > A > B > C$ . For EXE, the order is  $A > C > D > B$ . For LCOE, the order is  $A > C > D > B$ . The optimal operating-parameter schemes for CCR, EXE, and LCOE are A4-B2-C3-D1, A1-B3-C3-D5, and A1-B4-C3-D5, respectively. These conflicting optimal schemes reflect inherent multi-objective trade-offs in the system, indicating that it is still impossible to directly determine a universally optimal operating condition for the system. Therefore, an optimal compromise solution must be determined through multi-objective optimization.



(a) The influence of the factors on CCR.



(b) The influence of the factors on EXE.



(c) The influence of the factors on LCOE.

**Figure 3.** The influence of the factors on performance.

Table 6 presents the ANOVA results. For CCR, A and D exert statistically significant effects, while the effect of B approaches statistical significance. In contrast, C has no significant impact on CCR. For EXE, A, C, and D demonstrate high significance, while B exhibits no significance. For LCOE, A and C show high significance, whereas B and D exert

no significant influence. In summary, A is the most critical parameter across all three indicators. C is crucial to both *EXE* and *LCOE*. D mainly affects *CCR*. B only impacts *CCR*.

**Table 6.** ANOVA of performance indicators.

| Indicator   | Factor   | SS                     | DOFs | MS                     | F       | P      | Significance |
|-------------|----------|------------------------|------|------------------------|---------|--------|--------------|
| <i>CCR</i>  | A        | 0.226                  | 4    | 0.056                  | 14.317  | 0.001  | **           |
|             | B        | 0.079                  | 4    | 0.02                   | 5.025   | 0.025  | *            |
|             | C        | 0.013                  | 4    | 0.003                  | 0.827   | 0.543  |              |
|             | D        | 0.391                  | 4    | 0.098                  | 24.829  | <0.001 | **           |
|             | Residual | 0.032                  | 8    | 0.004                  |         |        |              |
| <i>EXE</i>  | A        | 0.04                   | 4    | 0.01                   | 781.931 | <0.001 | **           |
|             | B        | 1.545×10 <sup>-5</sup> | 4    | 3.861×10 <sup>-6</sup> | 0.305   | 0.867  |              |
|             | C        | 0.033                  | 4    | 0.008                  | 649.749 | <0.001 | **           |
|             | D        | 0.005                  | 4    | 0.001                  | 106.82  | <0.001 | **           |
|             | Residual | 0                      | 8    | 1.267×10 <sup>-5</sup> |         |        |              |
| <i>LCOE</i> | A        | 0.004                  | 4    | 0.001                  | 186.51  | <0.001 | **           |
|             | B        | 1.781×10 <sup>-5</sup> | 4    | 4.452×10 <sup>-6</sup> | 0.895   | 0.509  |              |
|             | C        | 0.002                  | 4    | 0.001                  | 105.945 | <0.001 | **           |
|             | D        | 2.129×10 <sup>-5</sup> | 4    | 5.323×10 <sup>-6</sup> | 1.071   | 0.431  |              |
|             | Residual | 3.978×10 <sup>-5</sup> | 8    | 4.972×10 <sup>-6</sup> |         |        |              |

SS: sum of squares; DOFs: degrees of freedom; MS: mean square; F: critical value; P: probability value.\* and \*\* represent significant differences ( $P \leq 0.05$ ) and extremely significant differences ( $P \leq 0.01$ ), respectively.

### 2.3. System Optimization Results

Based on the simulation results, a response surface modeling method is established to relate the operating parameters to the performance indicators. The fitting functions of the *CCR*, *EXE*, and *LCOE* are defined as  $R_1$ ,  $R_2$ , and  $R_3$ , and the relevant metrics of the fitting results are shown in Table 7.

**Table 7.** The parameters of models  $R_1$ ,  $R_2$ , and  $R_3$ .

| Model | RMSE   | $R^2$  | $R_{adj}^2$ |
|-------|--------|--------|-------------|
| $R_1$ | 0.0714 | 0.9242 | 0.8346      |
| $R_2$ | 0.0141 | 0.9971 | 0.9937      |
| $R_3$ | 0.0272 | 0.9879 | 0.9736      |

The calculated weights for *CCR*, *EXE*, and *LCOE* are 0.3457, 0.3358, and 0.3185, respectively. After determining the weights, the PSO algorithm is used to solve the single-objective optimization problem. The aggregate objective function is defined as the weighted sum of the three performance indicators based on the entropy weights obtained above. The optimization includes four decision variables, each of which is normalized to the range of [0, 1]. For the PSO parameters, the swarm size is set to 50, the maximum number of iterations is 200, and both the cognitive and social acceleration coefficients are set to 2.00 **Error! Reference source not found.**

The final results indicate that the system performs best at an  $R_{sc}$  of 4.37, an  $R_{cc}$  of 6.23, and  $R_{AE}$  of 1.39, and a  $T_{Ref}$  of 600 °C. Under this configuration, the system achieves a carbon-capture rate of 89.2%, an exergy efficiency of 45.7%, an energy efficiency of 95.4% and a levelized cost of exergy of 0.109 \$/ kWh.

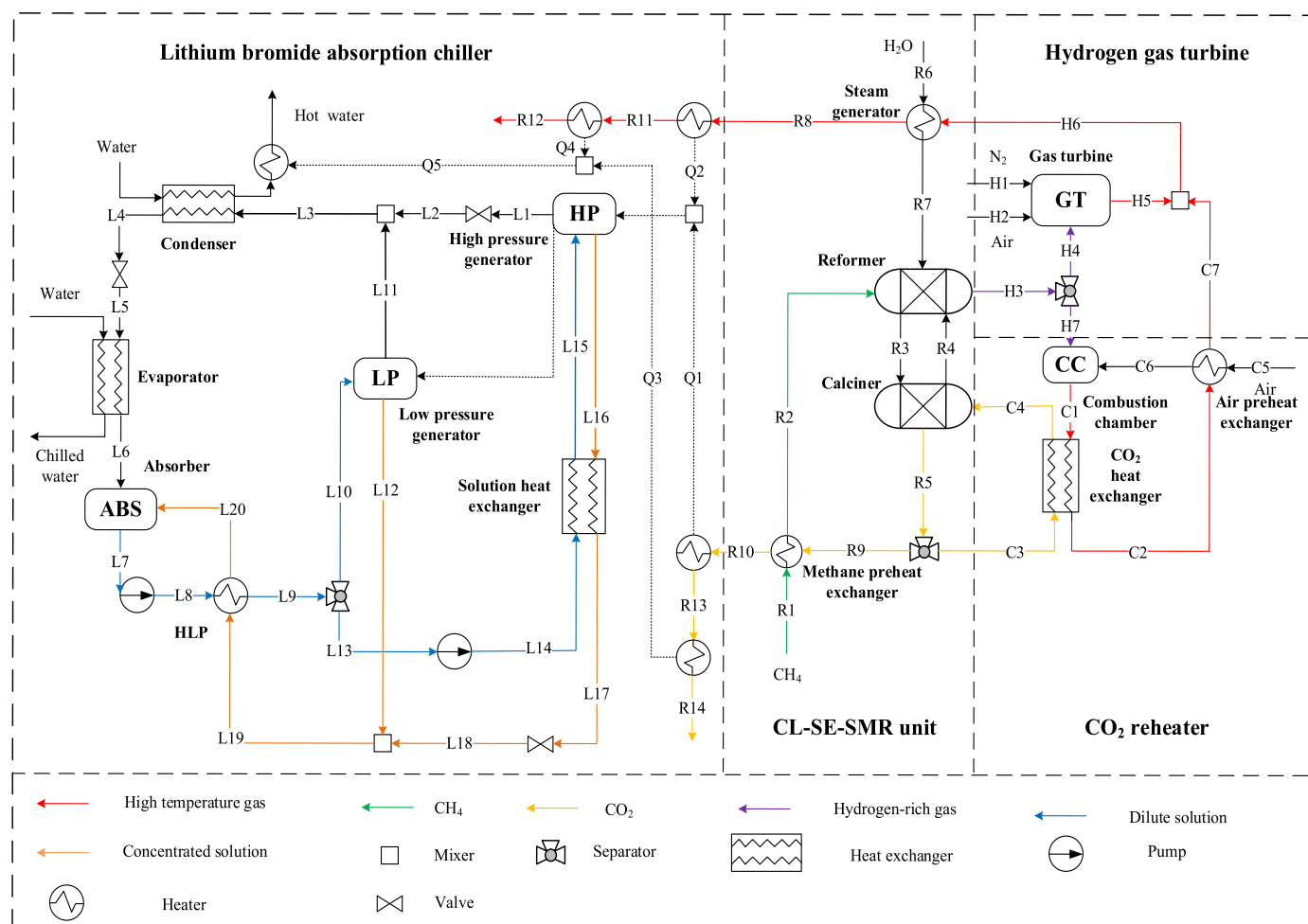
## 3. Materials and Methods

This section provides a detailed introduction to the LC-CCHP system and proposes a kinetic model for the CL-SE-SMR unit. Then, the detailed methods for energy analysis, exergy analysis, economic analysis, and multi-objective optimization are also presented.

### 3.1. System Flow-Sheet Description

The flow sheet of the proposed LC-CCHP system is depicted in Figure 4. It consists of a CL-SE-SMR unit, a lithium bromide absorption chiller, a hydrogen gas turbine and a CO<sub>2</sub> reheater. Water is converted into high-temperature steam in the steam generator, then enters the reformer to react with the preheated CH<sub>4</sub>. The reformer includes bed-material CaO and catalyst NiO. After the SE-SMR reaction is completed, the main products are hydrogen-rich gas and CaCO<sub>3</sub>, which are then separated. On the one hand, the CaCO<sub>3</sub> is sent to the calciner, where CaCO<sub>3</sub> is calcinated into CaO, and CO<sub>2</sub> gas is produced. Then, part of the hot CO<sub>2</sub> gas is recycled back to the calciner. The remaining CO<sub>2</sub> gas serves as a heat source for the cooling and heating sections. On the other hand, most of the hydrogen-rich gas is sent to the hydrogen gas turbine for power generation, producing high-temperature gas. A small portion of the hydrogen-rich gas is burned in the combustion chamber to heat the circulating CO<sub>2</sub> stream, thereby providing heat for the calciner. The lithium bromide absorption chiller mainly consists of a high-pressure generator and a low-pressure generator. The sensible heat contained in the high-temperature gas from the hydrogen gas turbine, the remaining CO<sub>2</sub> from the calciner and the flue gas from the CO<sub>2</sub> heat exchanger are extracted to the high-pressure generator and the low-pressure generator so that the concentrated lithium bromide solution is regenerated. The co-generated steam is then condensed and subsequently evaporated to supply cooling energy. Finally, the steam left the evaporator is absorbed by the concentrated lithium bromide solution. Note that the following simplifying assumptions are adopted throughout the system analysis:

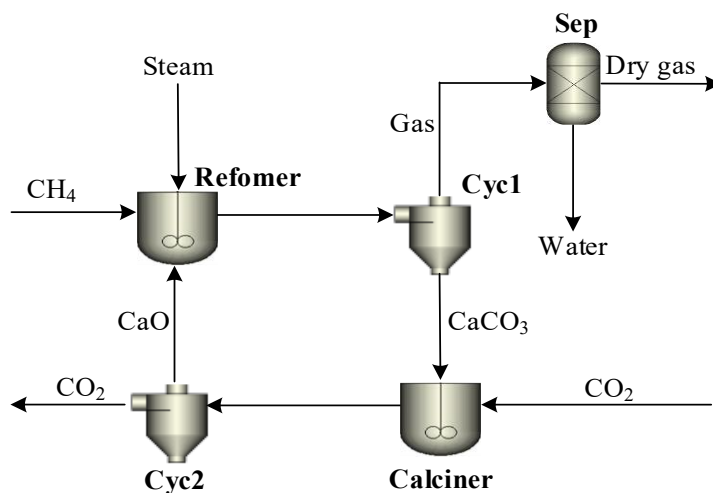
- (1) The LC-CCHP system operates at a steady state, and the reactors are adiabatic.
- (2) Pressure drops in the system pipelines are neglected.
- (3) The gas–solid multiphase hydrodynamics in the reactors are assumed to be homogeneously mixed, which is an important characteristic of the fluidized bed.
- (4) Catalyst deactivation over time, sorbent attrition and the associated loss of CaO-based material are ignored.



**Figure 4.** The flow sheet of the proposed LC-CCHP system.

### 3.2. Modeling of the CL-SE-SMR Unit

The CL-SE-SMR model is shown in Figure 5. The Ni-based catalyst and CaO-based sorbent serve as the bed material. The methane reforming reaction, the water–gas shift reaction and the carbonation reaction take place in the reformer, generating hydrogen-rich syngas and  $\text{CaCO}_3$ . After separation by the cyclone,  $\text{CaCO}_3$  is sent to the calciner, where it is calcinated at a high temperature to regenerate CaO. Then, the regenerated CaO circulates back to the reformer, while the released pure  $\text{CO}_2$  is discharged. The CaO/Ni mass ratio is set in the range of 3 to 6.



**Figure 5.** The flow sheet of the CL-SE-SMR model.

The external user-defined FORTRAN routine is used to implement the kinetic models **Error! Reference source not found.**. Among the numerous reaction kinetic models, the kinetic model for the SMR and water–gas shift reactions reported in Ref. **Error! Reference source not found.** is the most popular; the detailed model can be expressed as follows:

$$R_1 = \frac{1}{(DEN)^2} \frac{k_1}{P_{H_2}^{2.5}} \left( P_{CH_4} \cdot P_{H_2O} - \frac{P_{H_2}^3 P_{CO}}{K_1} \right) \quad (1)$$

$$R_2 = \frac{1}{(DEN)^2} \frac{k_2}{P_{H_2}} \left( P_{CO} \cdot P_{H_2O} - \frac{P_{H_2} P_{CO_2}}{K_2} \right) \quad (2)$$

$$DEN = 1 + K_{CO} P_{CO} + K_{H_2} P_{H_2} + K_{CH_4} P_{CH_4} + K_{H_2O} \frac{P_{H_2O}}{P_{H_2}} \quad (3)$$

where,  $P_i$  is the gas-phase partial pressure of component  $i$  ( $i$  denotes  $CH_4$ ,  $H_2O$ ,  $H_2$ ,  $CO_2$ , or  $CO$ ),  $K_1$  and  $K_2$  are the equilibrium constants, and  $k_1$  and  $k_2$  are the rate constants. The expressions of the kinetic parameters are listed in Table 8.

**Table 8.** Kinetic and equilibrium parameters.

| Kinetic Parameter                                                                                                                                                        | No.  |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
| $k_1 = 1.842 \times 10^{-4} \exp \left[ \frac{-240100}{R} \left( \frac{1}{T} - \frac{1}{648} \right) \right], \text{ kmol bar}^{0.5} / \text{kg}_{\text{cat}} \text{ h}$ | (4)  |
| $k_2 = 7.558 \exp \left[ \frac{-67130}{R} \left( \frac{1}{T} - \frac{1}{648} \right) \right], \text{ kmol} / \text{kg}_{\text{cat}} \text{ h bar}$                       | (5)  |
| $K_1 = 4.707 \times 10^{12} \exp \left( \frac{-224000}{RT} \right), \text{ bar}^2$                                                                                       | (6)  |
| $K_2 = 1.142 \times 10^{-2} \exp \left( \frac{37300}{RT} \right)$                                                                                                        | (7)  |
| $K_{CH_4} = 0.179 \exp \left[ \frac{38280}{R} \left( \frac{1}{T} - \frac{1}{823} \right) \right], \text{ bar}^{-1}$                                                      | (8)  |
| $K_{H_2O} = 0.4152 \exp \left[ \frac{-88680}{R} \left( \frac{1}{T} - \frac{1}{823} \right) \right]$                                                                      | (9)  |
| $K_{CO} = 40.91 \exp \left[ \frac{70650}{R} \left( \frac{1}{T} - \frac{1}{648} \right) \right], \text{ bar}^{-1}$                                                        | (10) |
| $K_{H_2} = 0.0296 \exp \left[ \frac{82900}{R} \left( \frac{1}{T} - \frac{1}{648} \right) \right], \text{ bar}^{-1}$                                                      | (11) |

To describe the carbonation of the CaO-based sorbents and the calcination rate of  $CaCO_3$ , an empirical equation is chosen **Error! Reference source not found.**. The reaction rate of calcium carbonation and the calcination rate can be calculated as follows:

$$R_{CB} = 5.007 \times 10^{-3} \exp \left( \frac{-20300}{RT} \right) (P_{CO_2} - P_{CO_2, EQ}) m_{CaO} \quad (12)$$

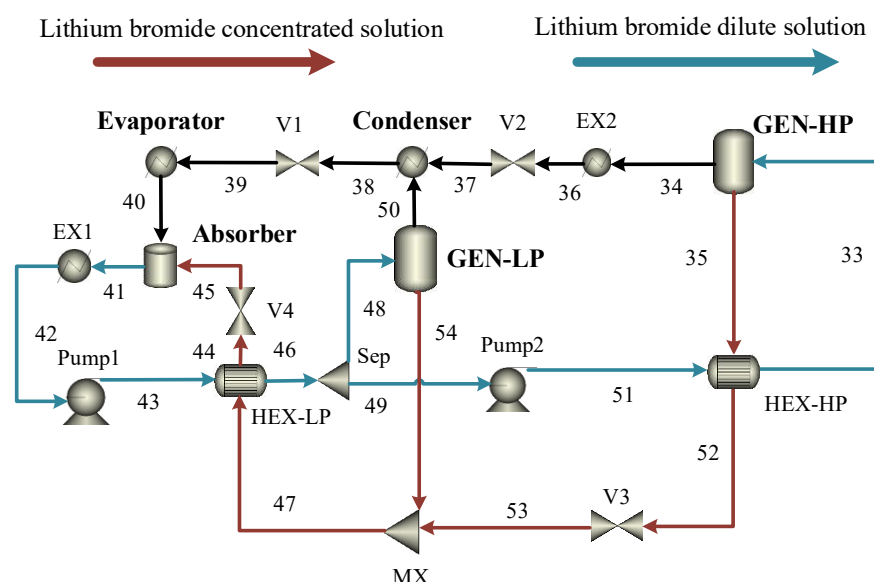
$$P_{CO_2, EQ} = 4.137 \times 10^7 \exp \left( \frac{20474}{T} \right) \quad (13)$$

$$R_{CAL} = 252015.2 \times \exp\left(\frac{-91700}{RT}\right) (1 - x_{CAL})^{2/3} (C_{CO_2, EQ} - C_{CO_2}) \quad (14)$$

where  $P_{CO_2, EQ}$  and  $P_{CO_2}$  denote the equilibrium  $CO_2$  pressure and  $CO_2$  partial pressure;  $m_{CaO}$  is the CaO-sorbent mass flow rate;  $x_{CAL}$  denotes the conversion of  $CaCO_3$ ; and  $C_{CO_2, EQ}$  and  $C_{CO_2}$  denote the  $CO_2$  concentrations at the equilibrium state and any other state, respectively.

### 3.3. Modeling of the Lithium Bromide Absorption Chiller

The model of the lithium bromide absorption chiller is shown in Figure 6. The refrigeration machine is driven by the heat of the high-temperature gas from the hydrogen gas turbine, the  $CO_2$  gas from the calciner in the CL-SE-SMR unit and the flue gas from the  $CO_2$  heat exchanger. The low-temperature steam is absorbed in the lithium bromide absorption chiller. The resulting dilute lithium bromide solution is then divided into two parts, which further enter the low-pressure and high-pressure regenerators separately to achieve regeneration. The produced steam is then mixed, depressurized and cooled before being absorbed by the absorber. Meanwhile, the regenerated lithium bromide solution is also mixed and stored in the absorber.



**Figure 6.** The flow sheet of the lithium bromide absorption refrigeration model.

The waste heat obtained by the high-pressure generator is defined as  $Q_{GEN-HP}$ . The condenser load and absorber load are defined as  $Q_{COND}$  and  $Q_{ABS}$  **Error! Reference source not found..**

$$Q_{COND} = m_{cool} (h_{38} - h_{37}) \quad (15)$$

$$Q_{ABS} = m_{cool} (h_{42} - h_{41}) \quad (16)$$

where  $m_{cool}$  represents the mass flow rate of the circulating solution,  $h_{37}$  and  $h_{38}$  are the specific enthalpies of the circulating working fluid entering and leaving the condenser, and  $h_{41}$  and  $h_{42}$  are the specific enthalpies of the circulating working fluid entering and leaving the heat exchanger. The cooling capacity of the evaporator ( $Q_{EVA}$ ) is defined as follows **Error! Reference source not found.:**

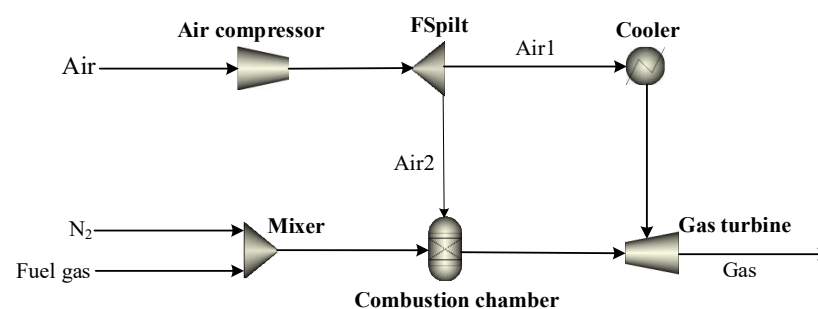
$$Q_{EVA} = m_{cw} (h_{40} - h_{39}) \quad (17)$$

where  $m_{cw}$  denotes the mass flow rate of the working fluid flowing through the evaporator and  $h_{39}$  and  $h_{40}$  are the specific enthalpies of the working fluid entering and leaving the evaporator. The refrigeration COP is defined as follows **Error! Reference source not found.**:

$$COP = \frac{Q_{EVA}}{Q_{GEN-HP}} \quad (18)$$

### 3.4. Modeling of the Hydrogen Gas Turbine Model

The hydrogen gas turbine model is shown in Figure 7. The hydrogen-rich fuel gas is mixed with nitrogen and enters the combustion chamber, where it burns with air. The compressed air is divided, with one portion serving as an oxidant in the combustion chamber and the other portion cooled and sent to the gas turbine to regulate temperature **Error! Reference source not found.**.



**Figure 7.** The flow sheet of the hydrogen gas turbine model.

### 3.5. Energy and Exergy Analyses

The exergy balance of the proposed LC-CCHP system is expressed as follows **Error! Reference source not found.**:

$$\sum_{steam} E_{X_{in}} + \sum_{fuel} E_{X_{in}} + \sum W_{in} + \sum E_{X_{in}}^Q = \sum_{gas} E_{X_{out}} + \sum E_{X_{out}}^Q + \sum W_{out} + E_{Cool} + E_{CO_2} + E_{Loss} \quad (19)$$

where  $E_{Cool}$  denotes the exergy of the system's cooling capacity,  $E_{CO_2}$  denotes the exergy of the discharged  $CO_2$  stream, and  $E_{Loss}$  denotes the system's exergy loss.

The energy efficiency (ENE) and exergy efficiency (EXE) of the LC-CCHP system are calculated as follows:

$$ENE = \frac{W_{out} + Q_{hot} + Q_{cool}}{m \cdot LHV_{fuel}} \times 100\% \quad (20)$$

$$EXE = \frac{W_{out} + E_{hot} + E_{cool}}{E_{X_{fuel}} + E_{water}^{in} + E_{air}} \times 100\% \quad (21)$$

where  $W_{out}$  denotes the system's output work, which consists of the output power of the hydrogen gas turbine, the power consumption of the compressor, and the power consumption of the two pumps of the lithium bromide absorption chiller.

### 3.6. Economic Analysis

The overall LC-CCHP system cost consists of the total investment cost (TIC) and the operation and maintenance (O&M) cost, which further includes the variable O&M (VOM) and fixed O&M (FOM) **Error! Reference source not found.**. The detailed economic models are listed in Tables 9–11. The  $\beta$  parameter in Table 2 is calculated as follows:

$$\beta = \left\{ \frac{i}{\left[1 - (1+i)^{-N}\right]} \right\} \quad (22)$$

The levelized cost of exergy (LCOE) is adopted as the key economic indicator, representing the ratio of the plant lifetime costs to the plant total lifetime exergy.

$$LCOE = \frac{\sum_{t=0}^N \frac{TIC|_t + O\&M|_t}{(1 + \text{discount rate})^t}}{\sum_{t=0}^N \frac{W_{net}|_t + E_{cool} + E_{hot}}{(1 + \text{discount rate})^t}} \quad (23)$$

where  $i$  is the yearly interest rate and  $N$  is the economical plant lifetime.

**Table 9.** Economic analysis method of the LC-CCHP system **Error! Reference source not found..**

| <b>TIC Calculation</b>                             | <b>Method</b>                                                             |
|----------------------------------------------------|---------------------------------------------------------------------------|
| Equipment cost ( $C_E$ )                           | See Table 10                                                              |
| Utilities and offsite units—installed cost ( $A$ ) | 25% of main equipment cost ( $\sum(C_E)$ )                                |
| Installed cost ( $IC$ )                            | $IC = \sum(C_E) + A$                                                      |
| Owners' cost and contingency ( $B$ )               | 15% $IC$                                                                  |
| Land purchase, permitting, surveying, etc. ( $C$ ) | 5% $IC$                                                                   |
| Total investment cost ( $TIC$ )                    | $TIC = IC + B + C$                                                        |
| <b>O&amp;M calculation</b>                         | <b>Method</b>                                                             |
| VOM costs ( $D$ )                                  | SUM (1:8)                                                                 |
| 1 Raw material (excluding fuel)                    | See Table 11                                                              |
| 2 Fuel cost                                        | See Table 11                                                              |
| 3 Maintenance                                      | 3% $TIC$                                                                  |
| 4 Operating supplies                               | 1% $TIC$                                                                  |
| 5 Patents & royalties                              | 3% $O\&M$                                                                 |
| 6 Operating labor                                  | 4 laborers                                                                |
| 7 Supervision/clerical                             | 10% operating labor                                                       |
| 8 Laboratory charges                               | 10% operating labor                                                       |
| Fixed charges ( $F1$ )                             | SUM (9:11)                                                                |
| 9 Capital charge                                   | $\beta \times TIC$                                                        |
| 10 Local taxes                                     | 2% $TIC$                                                                  |
| 11 Insurance                                       | 1% $TIC$                                                                  |
| Plant overhead ( $F2$ )                            | 5% $O\&M$                                                                 |
| General expenses ( $F3$ )                          | SUM (12:14)                                                               |
| 12 Marketing, sales, and distribution              | 2% $O\&M$                                                                 |
| 13 Administrative                                  | 2% $O\&M$                                                                 |
| 14 R&D                                             | 5% $O\&M$                                                                 |
| FOM costs ( $F = F1 + F2 + F3$ )                   | -                                                                         |
| CO <sub>2</sub> emission penalty ( $G$ )           | CO <sub>2</sub> emission in flue gases $\times$ ETS CO <sub>2</sub> price |
| $O\&M$                                             | $D + F + G$                                                               |

**Table 10.** The LC-CCHP system-component equipment costs.

| <b>Component</b> | <b>Equipment Cost Equation</b>                                                     | <b>Source</b>                             |
|------------------|------------------------------------------------------------------------------------|-------------------------------------------|
| Reformer         | $C_{Ref} = 130 \left( \frac{A_{Ref}}{0.093} \right)^{0.78} + 3240 (V_{Ref})^{0.4}$ | <b>Error! Reference source not found.</b> |
| Calciner         | $C_{Cal} = 590000 \cdot \left( \frac{m_{CaCO_3}}{59875} \right)^{0.67}$            | <b>Error! Reference source not found.</b> |

|         |                                                                     |                                    |
|---------|---------------------------------------------------------------------|------------------------------------|
| GT      | $C_{GT} = W_{GT} [1318.5 - 98.328 \ln(W_{GT})]$                     | Error! Reference source not found. |
| AEH     | $C_{AEH} = 2681 \cdot A_{AEH}^{0.59}$                               | Error! Reference source not found. |
| MEH     | $C_{MEH} = 2681 \cdot A_{MEH}^{0.59}$                               | Error! Reference source not found. |
| CBH     | $C_{CBH} = 2681 \cdot A_{CBH}^{0.59}$                               | Error! Reference source not found. |
| SG      | $C_{SG} = 2681 \cdot A_{SG}^{0.59}$                                 | Error! Reference source not found. |
| Heating | $C_{Heat} = 2681 \cdot A_{Heat}^{0.59}$                             | Error! Reference source not found. |
| Chiller | $C_{Cool} = Q_{Cool} \cdot (482 \cdot Q_{Cool}^{-0.07273} - 159.7)$ | Error! Reference source not found. |

**Table 11.** Basic economic assumptions for calculation.

| Item                      | Assumption       | Source                             |
|---------------------------|------------------|------------------------------------|
| CaO cost                  | 5.534 \$/t       | Error! Reference source not found. |
| CH <sub>4</sub> cost      | 9.51 \$/GJ       | Error! Reference source not found. |
| Ni cost                   | 21,800 \$/t      | -                                  |
| LiBr cost                 | 690.7 \$/t       | -                                  |
| Cooling water price       | 0.014 \$/t       | Error! Reference source not found. |
| Labor employee cost       | 11,634.2 \$/year | Error! Reference source not found. |
| ETS CO <sub>2</sub> price | 21.59 \$/t       | Error! Reference source not found. |
| CO <sub>2</sub> price     | 6.11 \$/t        | Error! Reference source not found. |
| Economical plant life     | 20 years         | Error! Reference source not found. |

### 3.7. System Optimization Methodology

To find the optimal condition of the LC-CCHP system, this section proposes a hybrid optimization that integrates an orthogonal experimental design, response surface fitting, the entropy weight method (EWM), and particle swarm optimization (PSO).

The steam-to-carbon molar ratio ( $R_{SC}$ ), the calcium-to-carbon mass ratio ( $R_{CC}$ ), the air-equivalency molar ratio for the hydrogen gas turbine ( $R_{AE}$ ), and the temperature of the SE-SMR reaction ( $T_{Ref}$ ) are selected as the optimization variables. The carbon-capture rate (CCR),  $EXE$ , and  $LCOE$  are selected as the performance indicators.

After applying the orthogonal experimental design to the selected optimization variables to obtain the experimental data, the response surface-fitting method is used to establish the relationship between the optimization variables and the optimization objective.

Common performance metrics for response surface models include the root mean square error (RMSE), the coefficient of determination ( $R^2$ ), and the adjusted coefficient of determination ( $R_{adj}^2$ ) **Error! Reference source not found.**, which can be calculated as follows:

$$RMSE = \frac{1}{k} \sqrt{\sum_{i=1}^k (y_i - \hat{y}_i)^2} \quad (24)$$

$$R^2 = 1 - \frac{\sum_{i=1}^k (y_i - \hat{y}_i)^2}{\sum_{i=1}^k (y_i - \bar{y})^2} \quad (25)$$

$$R_{adj}^2 = 1 - \frac{\sum_{i=1}^k (y_i - \hat{y}_i)^2 (k-1)}{\sum_{i=1}^k (y_i - \bar{y})^2 (k-p)} \quad (26)$$

where  $k$  is the number of tests,  $\bar{y}$  is the average value of all test points,  $y_i$  is the test value of the sampling point,  $\hat{y}_i$  is the calculated value of the response surface regression equation, and  $p$  is the number of experimental factors. Subsequently, the EWM is employed to determine the weight of each indicator **Error! Reference source not found.**. The calculation formulas for entropy weight are expressed as follows **Error! Reference source not found.**:

$$w_i = \frac{1 - H_i}{m - \sum_{i=1}^m H_i} \quad (27)$$

$$H_i = -\frac{1}{\ln n} \sum_{j=1}^n f_{ij} \ln f_{ij} \quad (28)$$

$$f_{ij} = \frac{r_{ij}}{\sum_{j=1}^n r_{ij}} \quad (29)$$

where  $H_i$  is the information entropy and  $f_{ij}$  is the characteristic proportion.

## 4. Conclusions

To reduce carbon discharge and improve the thermal efficiency of a carbon combined cooling, heating and power (CCHP) system, a novel low-carbon CCHP (LC-CCHP) system is proposed in this work, and the corresponding system model is built. To improve the system model's prediction accuracy, a detailed kinetic model for the CL-SE-SMR unit, the key unit of the LC-CCHP system, is developed. To find the optimal operating conditions of the LC-CCHP system, a multi-objective optimization is implemented. Finally, the following promising conclusions are obtained:

- (1) The proposed LC-CCHP system runs stably under the given ranges of operational conditions. The kinetic model for the CL-SE-SMR unit is reliable and more accurate than the thermodynamic model.
- (2) The proposed LC-CCHP system performs best at a steam-to-carbon molar ratio of 4.37, a calcium-to-carbon mass ratio of 6.23, an air-equivalency molar ratio of 1.39 for a hydrogen gas turbine, and a temperature of 600 °C for an SE-SMR reaction.
- (3) Under the optimal configuration, the LC-CCHP system achieves a carbon-capture rate of 89.2%, an exergy efficiency of 45.7%, an energy efficiency of 95.4% and a levelized cost of exergy of 0.109 \$/ kWh.
- (4) From an implementation perspective, the proposed LC-CCHP system is most suitable for industrial parks that have simultaneous demands for electricity, heating, and

cooling and where a consistent supply of natural gas and CO<sub>2</sub> storage or utilization infrastructure is available.

**Author Contributions:** Conceptualization, J.L. and L.Y.; methodology, J.L. and L.Y.; software, J.L., L.Y. and Y.D.; validation, J.L., S.Q. and Z.J.; investigation, L.W., S.Q., Z.F. and Z.R.; writing—original draft preparation, J.L., L.Y. and S.Q.; writing—review and editing, L.Y. and L.W.; visualization, J.L. and S.C.; supervision, L.Y. and L.W.; funding acquisition, L.Y. and L.W. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the Nuclear Industry Engineering Research and Design Co., Ltd. (grant number CNNC-SJY-KY-2025-001).

**Data Availability Statement:** The data presented in this study are available upon request from the corresponding author.

**Conflicts of Interest:** The authors declare that this study received funding from the Nuclear Industry Engineering Research and Design Co., Ltd. The funder had the following involvement with the study: validation and visualization.

## References

1. Du, J.; Guo, J. Analysis of multi-cascade CCHP system with gas turbine bypass extraction air energy storage. *Appl. Therm. Eng.* **2023**, *232*, 121021.
2. Bevacqua, E.; Schleussner, C.F.; Zscheischler, J. A year above 1.5 °C signals that Earth is most probably within the 20-year period that will reach the Paris Agreement limit. *Nat. Clim. Change* **2025**, *15*, 262–265.
3. Feng, L.; Dai, X.; Mo, J.; Shi, L. Analysis of energy-matching performance and suitable users of conventional CCHP systems coupled with different energy storage systems. *Energy Convers. Manag.* **2019**, *200*, 112093.
4. Lu, X.; Gang, W.; Cai, S.; Tu, Z. Advanced optimization framework for methane-fueled solid oxide fuel cell combined cooling heating and power system based on marine cyclic loads. *Appl. Therm. Eng.* **2026**, *296*, 130808.
5. Khalvan, A.; Mehregan, M.; Kayhani, M.H.; Sheykhi, M. 4E analysis of an advanced CCHP configuration with gas turbine prime mover incorporating inlet cooling, a modified compression refrigeration cycle and energy storage with renewable energy sources. *Results Eng.* **2025**, *29*, 108801.
6. Chahartaghi, M.; Namdarian, R.; Hashemian, S.M.; Malek, R.; Hashemi, S. Energy, exergy, economic, and environmental (4E) analyses and optimization of a CCHP system with steam turbine. *Energy Sci. Eng.* **2021**, *9*, 897–915.
7. Lucarelli, G.; Genovese, M.; Florio, G.; Fragiaco, P. 3E (energy, economic, environmental) multi-objective optimization of CCHP industrial plant: Investigation of the optimal technology and the optimal operating strategy. *Energy* **2023**, *278*, 127837.
8. Hai, T.; Asadollahzadeh, M.; Chauhan, B.S.; Al-Ebrahim, M.A.; Bunian, S.; Eskandarzade, A.; Salah, B. Machine learning optimization and 4E analysis of a CCHP system integrated into a greenhouse system for carbon dioxide capturing. *Energy* **2024**, *309*, 133028.
9. Liu, B.; Lian, Y.; Li, S.; Deng, S.; Zhao, L.; Chen, B.; Wang, D. Experimental investigation on separation and energy-efficiency performance of temperature swing adsorption system for CO<sub>2</sub> capture. *Sep. Purif. Technol.* **2019**, *227*, 115670.
10. Akbarnataj, K.; Saffaripour, M.; Houshfar, E. Novel design of a CCHP system to boost nearly zero-carbon building concept. *Energy Convers. Manag.* **2024**, *309*, 118468.
11. Akbarnataj, K.; Saffaripour, M.; Houshfar, E. Membrane-based CO<sub>2</sub> capture integrated with CCHP for a nearly zero-carbon building. *Build. Environ.* **2025**, *273*, 112738.
12. Giuliano, A.D.; Gallucci, K. Sorption enhanced steam methane reforming based on nickel and calcium looping: A review. *Chem. Eng. Process. Process Intensif.* **2018**, *130*, 240–252.
13. Zhang, X.; Guo, J.; Guo, Y.; Yu, Y.; Liu, X.; Zhang, Z.; Zhao, C. Integrated CO<sub>2</sub> capture and utilization via calcium-looping and dry reforming of methane: A review on sintering and coke deposition, mitigation strategies and techno-economic analysis. *Fuel* **2026**, *408*, 137706.
14. Yari, M.; Zare, A.A.D. Thermodynamic and economic analysis of a nuclear-based, zero-carbon multi-generation system with sorption enhanced reforming. *Energy* **2025**, *338*, 138965.
15. Zare, A.A.D.; Yari, M.; Ghaebi, H. Pathways to blue hydrogen with near-zero net emissions: Thermodynamic and Techno-Economic insights into SE-SMR–CLC–PAFC system. *Energy Convers. Manag.* **2026**, *358*, 121351.

16. Huang, S.; Duan, L.; Wang, Q.; Huang, L.; Zhang, H. Thermodynamic analysis of a CCHP system with hydrogen production process by methane reforming enhanced by solar-assisted chemical looping adsorption. *Appl. Therm. Eng.* **2024**, *248*, 123137.
17. Carlo, A.D.; Bocci, E.; Zuccari, F.; Era, A.D. Numerical investigation of sorption enhanced steam methane reforming process using computational fluid dynamics Eulerian–Eulerian Code. *Ind. Eng. Chem. Res.* **2010**, *49*, 1561–1576.
18. Yan, L.; Jia, Z.; Liu, Y.; Wang, L.; Shi, J.; Qian, M.; He, B. On the Modeling of Continuous H<sub>2</sub> Production by Sorption-Enhanced Steam Methane Reforming. *Catalysts*, **2025**, *15*, 246. <https://doi.org/10.3390/catal15030246>.
19. García-Lario, A.L.; Aznar, M.; Martinez, I.; Grasa, G.S.; Murillo, R. Experimental study of the application of a NiO/NiAl<sub>2</sub>O<sub>4</sub> catalyst and a CaO-based synthetic sorbent on the Sorption Enhanced Reforming process. *Int. J. Hydrog. Energy* **2015**, *40*, 219–232.
20. Herold, K.E.; Radermacher, R.; Klein, S.A. *Absorption Chillers and Heat Pumps*; CRC Press: Boca Raton, FL, USA, 2016.
21. Xu, L.; Huang, Y.; Li, G.; Zou, M. Simulation and analysis of Double-effect Absorption Refrigeration Unit based on Aspen Plus. *Build. Energy Environ.* **2021**, *40*, 16–20.
22. Lan, W.; Chen, G.; Zhu, X.; Wang, X.; Liu, C.; Xu, B. Biomass gasification-gas turbine combustion for power generation system model based on ASPEN PLUS. *Sci. Total Environ.* **2018**, *628–629*, 1278–1286.
23. Yan, L.; Cao, Y.; Wang, Z.; He, B. On a novel carbon-negative IGCC system with cascade CO<sub>2</sub> combined cycle. *Energy Convers. Manag.* **2020**, *221*, 113202.
24. Wu, Z.; Zhu, P.; Yao, J.; Zhang, S.; Ren, J.; Yang, F.; Zhang, Z. Combined biomass gasification, SOFC, IC engine, and waste heat recovery system for power and heat generation: Energy, exergy, exergoeconomic, environmental (4E) evaluations. *Appl. Energy* **2020**, *279*, 115794.
25. Osat, M.; Shojaati, F.; Osat, M. A solar-biomass system associated with CO<sub>2</sub> capture, power generation and waste heat recovery for syngas production from rice straw and microalgae: Technological, energy, exergy, exergoeconomic and environmental assessment. *Appl. Energy* **2023**, *340*, 120999.
26. You, H.; Han, J.; Liu, Y.; Chen, C.; Ge, Y. 4E analysis and multi-objective optimization of a micro poly-generation system based on SOFC/MGT/MED and organic steam ejector refrigerator. *Energy* **2020**, *206*, 118122.
27. Moghimi, M.; Emadi, M.; Ahmadi, P.; Moghads, H. 4E analysis and multi-objective optimization of a CCHP cycle based on gas turbine and ejector refrigeration. *Appl. Therm. Eng.* **2018**, *141*, 516–530.
28. Tang, K.; Li, Z.; Luo, L.; Liu, B. Multi-strategy adaptive particle swarm optimization for numerical optimization. *Eng. Appl. Artif. Intell.* **2015**, *37*, 9–19.
29. Xu, J.; Froment, G.F. Methane steam reforming, methanation and water-gas shift: I. Intrinsic kinetics. *AIChE J.* **1989**, *35*, 88–96.
30. Yan, L.; He, B. On a clean power generation system with the co-gasification of biomass and coal in a quadruple fluidized bed gasifier. *Bioresour. Technol.* **2017**, *235*, 113–121.
31. Mehrpooya, M.; Sayyad, S.; Zonouz, M.J. Energy, exergy and sensitivity analyses of a hybrid combined cooling, heating and power (CCHP) plant with molten carbonate fuel cell (MCFC) and Stirling engine. *J. Clean. Prod.* **2017**, *148*, 283–294.
32. Zhang, Y.; Liang, T.; Yang, K. An integrated energy storage system consisting of Compressed Carbon dioxide energy storage and Organic Rankine Cycle: Exergoeconomic evaluation and multi-objective optimization. *Energy* **2022**, *247*, 123566.
33. Abanades, J.C. The maximum capture efficiency of CO<sub>2</sub> using a carbonation/calcination cycle of CaO/CaCO<sub>3</sub>. *Chem. Eng. J.* **2002**, *90*, 303–306.
34. Cormos, C.C.; Vatopoulos, K.; Tzimas, E. Assessment of the consumption of water and construction materials in state-of-the-art fossil fuel power generation technologies involving CO<sub>2</sub> capture. *Energy* **2013**, *51*, 37–49.
35. Liu, Y.; Han, J.; You, H. Exergoeconomic analysis and multi-objective optimization of a CCHP system based on SOFC/GT and transcritical CO<sub>2</sub> power/refrigeration cycles. *Appl. Therm. Eng.* **2023**, *230*, 120686.
36. Saadia, S.; Houcine, B.; Abdelhak, B.; Ahmed, M. Optimization of factors affecting biogas production from dairy wastewater using Response Surface Methodology and its kinetic and microbial analysis. *Results Eng.* **2025**, *26*, 104781.
37. Zhao, Q.; Ma, Z.; Wei, S.; Lu, M.; Xu, H. Development, modeling and optimization of a solar-hydrogen-electricity-thermal-based integrated energy system for remote cold regions. *Energy Convers. Manag.* **2026**, *347*, 120582.
38. Ouyang, Y.; Shen, Z.; Zuo, Q.; Li, Q.; Ma, Y.; Zhang, H. Investigation of rotary proton exchange membrane fuel cell performance optimization based on orthogonal experiment and entropy weight method. *Appl. Therm. Eng.* **2025**, *272*, 126362.

**Disclaimer/Publisher’s Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.