

## Article

# Design and Optimization of Solar Green Methanol Production System Based on NSGA-II and AHP-TOPSIS Method

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## Abstract

Electrochemical reduction of carbon dioxide (CO<sub>2</sub>RR) to methanol represents a promising approach for sustainable methanol production. Despite this potential, current technological limitations constrain both economic viability and environmental benefits. This research introduces a solar-driven multigeneration system that integrates CO<sub>2</sub>RR to enable the coproduction of electricity and green methanol. A comprehensive energy integration analysis was conducted, alongside a combined techno-economic, energy-efficiency, and environmental (3E) assessment. Multiobjective optimization was conducted using the Non-dominated Sorting Genetic Algorithm-II (NSGA-II). For solution selection, the analytic hierarchy process (AHP) was integrated with the order preference by similarity to ideal solution (TOPSIS) methodology. Results indicate that the integrated system achieves a 4.2% reduction in total utility consumption. The optimal levelized cost of methanol (LCOM), net specific carbon emissions (Net<sub>SCE</sub>), and energy efficiency ( $\eta_{EN}$ ) are USD 0.526/kg,  $-1.16$  kg CO<sub>2</sub>SCE/kg CH<sub>3</sub>OH, and 6.52%, respectively. LCOM decreases by 30.6% compared to the initial system, Net<sub>SCE</sub> increases by 3.44%, and  $\eta_{EN}$  improves by 5.84%. Under optimal operating conditions, CH<sub>3</sub>OH production capacity and grid power consumption reach 45.27 tons/day and 475.83 MWh/day, respectively. The system does not currently meet the commercial threshold and becomes economically viable only if the electricity price exceeds USD 0.223/kWh. This study provides a valuable reference for future research in system-level integration of CO<sub>2</sub>RR and multiobjective solution selection.

**Keywords:** CO<sub>2</sub>RR; NSGA-II; AHP-TOPSIS method; CSP



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## 1. Introduction

Methanol is a fundamental organic chemical feedstock and a clean energy carrier in modern industry, occupying a central position within the chemical industry chain. Classification of methanol is based on the carbon-emission intensity of its production process: black methanol (coal-based), grey methanol (natural gas-based), blue methanol (produced from blue hydrogen and carbon dioxide), and green methanol (derived from biomass and renewable energy). Conventional synthesis of methanol from natural gas and coal results in substantial greenhouse gas emissions. In contrast, green methanol produced from biomass and renewable energy helps achieve the “dual carbon goals”. Table 1 provides an overview of current research on green methanol production. Most studies focus on thermocatalytic CO<sub>2</sub> hydrogenation coupled with water electrolysis, a process characterized by high production costs and operational complexity (the market price of green methanol is USD 0.5/ton [1]). Alternatively, methanol synthesis from

syngas via biomass gasification is associated with significant uncertainties. Furthermore, comprehensive research on alternative technical pathways remains limited.

**Table 1.** An overview of current research on green methanol production.

| Reaction Type                                                          | Cost of Methanol/(USD/kg) | Year | Reference |
|------------------------------------------------------------------------|---------------------------|------|-----------|
| Thermal catalytic CO <sub>2</sub> hydrogenation& electrolysis of water | 0.823                     | 2026 | [2]       |
| Biomass gasification                                                   | 0.294                     | 2025 | [3]       |
| Thermal catalytic CO <sub>2</sub> hydrogenation                        | 0.984                     | 2025 | [4]       |
| Thermal catalytic CO <sub>2</sub> hydrogenation                        | 1.393                     | 2025 | [5]       |
| Thermal catalytic CO <sub>2</sub> hydrogenation& electrolysis of water | 1.130                     | 2024 | [6]       |
| Thermal catalytic CO <sub>2</sub> hydrogenation& electrolysis of water | 0.794                     | 2021 | [7]       |

The carbon dioxide electrochemical reduction reaction (CO<sub>2</sub>RR) represents a promising approach for sustainable methanol production, due to its mild reaction conditions and compatibility with renewable energy sources [8]. Seshadri et al. [9] developed a homogeneous electrocatalyst with a low overpotential, enabling the first direct conversion of CO<sub>2</sub> to methanol and laying the foundation for subsequent research. Payra et al. [10] investigated the CO<sub>2</sub>RR-to-methanol process using carbon-supported intermetallic PtZn nanoalloys, achieving a Faraday efficiency of 81.4% for methanol. Rihm et al. [11] presented a comprehensive micro-reaction kinetic model for CO<sub>2</sub>RR, providing a mathematical framework for optimizing electrolyzer performance. Currently, the energy efficiency of one-step methanol synthesis via CO<sub>2</sub>RR is approximately 14% [12]. To assess the economic and environmental viability of this technology, Adnan et al. [1] performed a financial analysis of three methanol synthesis pathways using carbon dioxide as the feedstock and electrochemical processes. Their results indicate that, under current technical conditions, the levelized cost of methanol is USD 1585/ton CH<sub>3</sub>OH. Under optimistic future technical scenarios, the levelized cost could decrease to USD 400/ton CH<sub>3</sub>OH, with a carbon dioxide emission of −0.02 kg CO<sub>2</sub>e/kg CH<sub>3</sub>OH. The primary factors contributing to the elevated levelized cost are the high price of the electrolyzer stack, which accounts for 82% of the investment cost, and electricity expenses, which represent 55% of the operating cost [8].

Li et al. [8] proposed and evaluated a conceptual scheme that integrates CO<sub>2</sub> capture, biomass gasification, and CO<sub>2</sub>RR using an ionic liquid electrolyte. Their findings indicate that, under both current and projected conditions, total production costs can be reduced by 28% to 66%. Furthermore, Li et al. [13] integrated black liquor, a waste product from pulp mills, with CO<sub>2</sub>RR. The results suggest that, under optimistic scenarios, the levelized cost of methanol for one-step methanol synthesis via CO<sub>2</sub>RR is USD 445/ton CH<sub>3</sub>OH (380 €/ton CH<sub>3</sub>OH). The existing literature primarily addresses reducing the levelized cost of methanol (LCOM) through system integration of material recovery and reuse in reaction and separation processes. In contrast, energy integration between systems has received limited attention.

Concentrated solar power (CSP) is a technology that converts solar energy into electricity. Compared with other renewable energy technologies, CSP offers high power quality, energy storage capability, and peak shaving potential. The primary power cycles implemented in CSP are the steam Rankine cycle (SRC) and the Brayton cycle. The steam Rankine cycle uses water as the working fluid, operates through a straightforward and efficient process, and is widely adopted in power generation. The Brayton cycle, particularly the supercritical carbon dioxide Brayton cycle, is considered a promising alternative to the traditional steam Rankine cycle. Both cycles generate low-temperature heat sources following compression or re-compression of the working medium. The Organic Rankine Cycle (ORC) is an effective method for waste heat recovery and improves the thermal

efficiency of internal combustion engines. Peng et al. [14] evaluated the performance of various working fluids for low-temperature waste heat resources in the range of 90–240 °C. Their findings indicate that the optimal evaporation and condensation temperatures are 120–140 °C and 20–30 °C, respectively, and that chlorofluorocarbon working fluids achieve higher thermal efficiency than other alternatives. Currently, most commercial CSP plants employ the Rankine cycle, with steam turbines converting solar energy into electricity [15]. Due to its superior heat transfer performance, high heat capacity, and elevated operating temperature, molten salt is expected to remain the primary heat storage medium for CSP plants over the next five to seven years. Commercial molten nitrate salt, known as solar salt, consists of 60% sodium nitrate and 40% potassium nitrate. Most CSP plants using molten salt storage operate at 293–565 °C to maintain a sufficient safety margin above the freezing point. These studies demonstrate that significant low-temperature thermal resources are available at the energy supply end. On the energy-demand side, electrochemical reactions also require low-temperature heat to complete product separation. Therefore, there is considerable potential for energy integration between CSP generation and CO<sub>2</sub>RR-based methanol production systems.

Multiobjective optimization addresses the challenge of optimizing integrated systems characterized by multiple interacting indicators and inherent trade-offs. This methodology aims to optimize multiple conflicting objective functions simultaneously, yielding a Pareto solution set, and is widely applied to such complex problems. Zhang [16] optimized three objective functions for a solar-electricity-hydrogen polygeneration system using the Non-dominated Sorting Genetic Algorithm-II (NSGA-II), thereby identifying optimal comprehensive performance and relevant system parameters. In many previous studies, the final solution is selected based on the spatial distance among multiobjective optimization results. This process introduces subjectivity and may overlook deviations caused by data dispersion. Yang et al. [17] developed a Kriging surrogate model for the multiobjective optimization of a battery thermal management system and utilized the entropy weight technique for order preference by similarity to ideal solution (TOPSIS) to screen Pareto-optimal solutions. The entropy weight method uses information entropy to measure indicator dispersion and assign weights accordingly. Although this method can reduce subjectivity, it requires extensive sample data and may neglect the intrinsic importance of individual indicators. The analytic hierarchy process (AHP) is a multicriteria decision analysis method that integrates subjective judgments and objective data within a unified analytical framework. Therefore, a selection method that combines AHP and TOPSIS will be applied for selecting the Pareto solution set.

A novel approach to green methanol production will be proposed, using a polygeneration system that integrates solar heat collection, Steam Rankine Cycle (SRC) power generation, Organic Rankine Cycle (ORC) power generation, and CO<sub>2</sub>RR-based methanol synthesis. A simulation and analysis model is developed to evaluate system performance from energy, economic, and environmental perspectives. Multiobjective optimization is conducted using the NSGA-II algorithm, and the AHP-TOPSIS method is applied to identify the optimal Pareto solution. This methodology enables the determination of the system's optimal operating parameters and minimizes the levelized cost of green methanol.

## 2. Methods

### 2.1. Process Description

The system consists of a solar collector subsystem, an SRC power generation subsystem, an ORC power generation subsystem, a CO<sub>2</sub>RR subsystem, and a product separation subsystem, as illustrated in Figure 1.

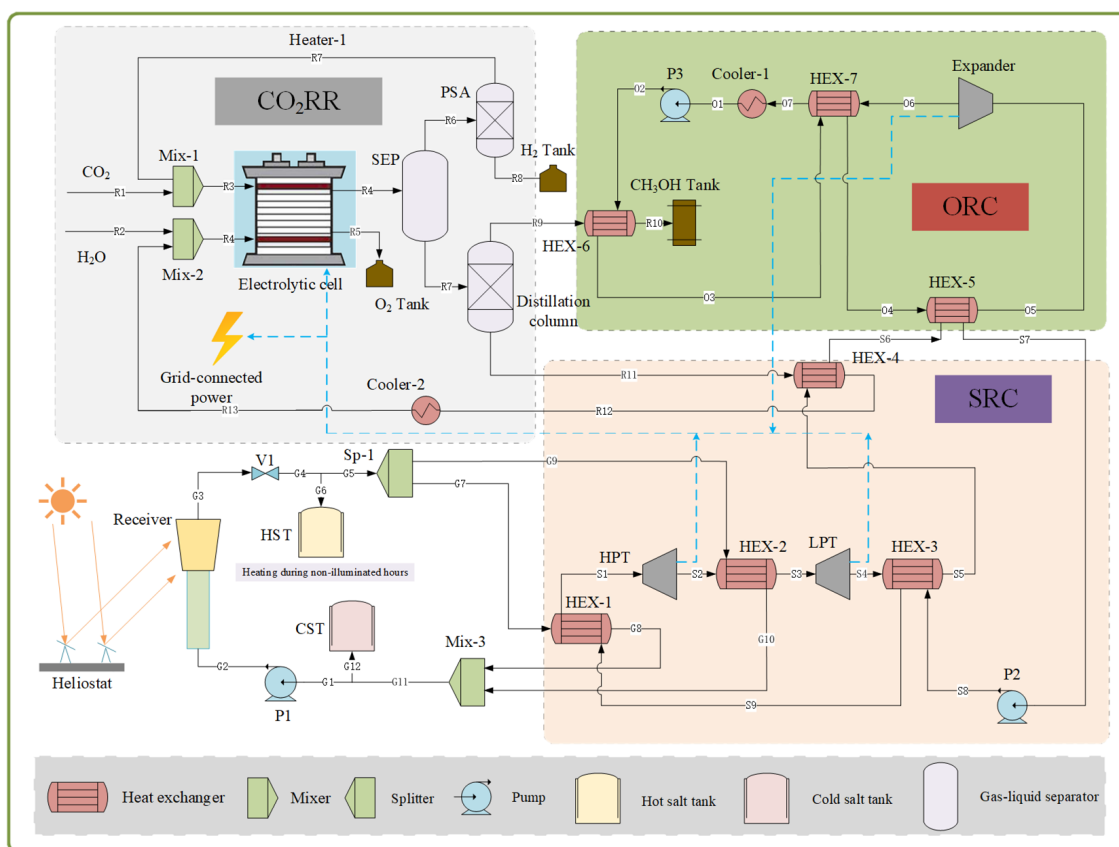


**Figure 1.** Flowchart of the hybrid system.

Molten salt is transported to the top of the receiver tower by pump P1, where it is heated by solar energy reflected from the heliostats. The heated molten salt is delivered from the bottom of the tower to the pressure-reducing valve V1. Following decompression, a portion of the molten salt flows into the hot salt tank (HST) to provide heat during periods without illumination, while the remainder passes through heat exchangers (HEX-1, HEX-2) before entering the cold salt tank (CST). The circulating medium of the SRC is pressurized by pump P2, and exchanges heat with the regenerator (HEX-3) and the heat exchanger (HEX-1). The resulting high-temperature, high-pressure steam drives the high-pressure turbine (HPT) to generate power. The outlet steam subsequently exchanges heat via heat exchanger (HEX-2) to drive the low-pressure turbine (LPT), and the resulting low-temperature, low-pressure steam passes through the regenerator (HEX-3) to supply waste heat to the distillation column reboiler (HEX-4) and evaporator (HEX-5) before being cooled. In the ORC, the working fluid R245fa is pressurized by pump P3 and subsequently exchanges heat in the condenser (HEX-6), the regenerator (HEX-7), and the evaporator (HEX-5). The resulting R245fa vapor powers the expander (EXP) to generate work, after which it transfers heat in the regenerator (HEX-7) and is cooled in Cooler-1. Only oxygen is generated exclusively at the anode of the electrolyzer and is directed to the storage tank, while the gas-liquid mixture ( $\text{CO}_2$ ,  $\text{H}_2$ ,  $\text{H}_2\text{O}$ ,  $\text{CH}_3\text{OH}$ ) produced at the cathode first undergoes gas-liquid two-phase separation (SEP). The gas phase is separated using pressure swing adsorption (PSA), with  $\text{CO}_2$  recycled to the reaction system and  $\text{H}_2$  stored in a tank. The liquid phase is separated by a distillation column. Electrical energy generated by the turbines and the expander is first supplied to the electrolyzer, with any surplus delivered to the power grid.

The system operates using solar energy, which is inherently intermittent and unstable. These characteristics may result in interruptions or fluctuations in production, potentially

disrupting stable system operation. As the primary objective of this study is to evaluate the potential for system energy integration, the intermittency issue is mitigated by incorporating molten salt storage tanks to supply heat during periods without solar illumination. The instability issue is addressed by adopting reference values for relevant parameters based on published literature.

## 2.2. System Model

The model was developed in Aspen Plus V12 using the NRTL property method and the following assumptions:

- (1) The system is assumed to operate under steady-state conditions, with all chemical reactions reaching thermodynamic equilibrium;
- (2) Fluid friction losses are neglected;
- (3) Standard temperature and pressure are set at 25 °C and  $1 \times 10^5$  Pa;
- (4) Changes in kinetic and potential energy are considered negligible;
- (5) The reaction conversion rate is set at 50%. Cathode products consist exclusively of methanol and hydrogen. The feed carbon dioxide and the oxygen generated at the anode are both assumed to be 100% pure.

In the simulation and optimization stages, the PSA separation process was simplified. The influence of PSA separation efficiency on system performance was evaluated through sensitivity analysis. Detailed findings are provided in Figure S1 in the Supplementary Materials. The analysis indicates that separation efficiency affects the relevant research parameters by less than 0.2%. In alignment with previous studies [18], a separation efficiency of 100% was assumed for the initial analysis.

### 2.2.1. CSP Subsystem

Given that solar radiation varies sinusoidally over time and the illumination period is 12 h, the heat energy received by the receiver tower and heliostats is calculated using Equations (1) and (2) [18].

$$\dot{Q}_{Solar} = A_{Helio} \times N \times DNI \quad (1)$$

$$\dot{Q}_{Heliostats} = \dot{Q}_{Solar} \times \eta_{Opt} \quad (2)$$

where  $A_{Helio}$  refers to the area of a single heliostat,  $m^2$ ;  $N$  denotes the total number of heliostats;  $DNI$  indicates the direct normal irradiance,  $W/m^2$ ; and  $\eta_{Opt}$  represents the optical efficiency of the heliostat.

The heat absorbed by the molten salt is determined by Equation (3):

$$\dot{Q}_{abs} = \dot{Q}_{Heliostats} - \dot{Q}_{loss} = \dot{m}(\dot{h}_{G3} - \dot{h}_{G2}) \quad (3)$$

where  $\dot{h}_{G2}$  and  $\dot{h}_{G3}$  denote the enthalpy of the molten salt stream.  $\dot{Q}_{loss}$  represents the heat loss of the central receiver tower, kW. When considering only convective heat transfer and heat conduction,  $\dot{Q}_{loss}$  is calculated by Equations (4)–(7).

$$\dot{Q}_{loss} = \dot{Q}_{loss,conv} + \dot{Q}_{loss,rad} \quad (4)$$

$$\dot{Q}_{loss,conv} = h_{air} A_r (T_{surf} - T_0) \quad (5)$$

$$\dot{Q}_{loss,rad} = \sigma \epsilon (T_{surf}^4 - T_0^4) \quad (6)$$

$$\alpha_{air} = 10.45 - V_a + 10\sqrt{V_a} \quad (7)$$

where  $h_{air}$  denotes the convective heat transfer coefficient between reflected solar radiation and air,  $\text{kW}/(\text{m}^2 \cdot \text{K})$ ;  $\varepsilon$  represents the emissivity of the receiver;  $\sigma$  is the Stefan-Boltzmann constant, valued at  $5.67 \times 10^{-8} \text{ W}/(\text{m}^2 \cdot \text{K}^4)$ ;  $A_r$  refers to the receiving area of the receiver,  $\text{m}^2$ ;  $T_{surf}$  represents the surface temperature of the receiver,  $\text{K}$ ;  $V_a$  denotes the wind speed,  $\text{m}/\text{s}$ .

The height of the heat collection tower (HCT) is determined using Equation (8). The flow rate of the molten salt stream (G5) under operating conditions is calculated using Equation (9).

$$H_t = 36.7 \left( \frac{\dot{Q}_{abs}}{1000} \right)^{0.288} \quad (8)$$

$$\dot{m}_{G5} = \frac{t_{Solar} \dot{m}_{G2}}{24} \quad (9)$$

Equations (1)–(9) were implemented in Fortran and embedded in Aspen Plus to simulate the solar heat collection system and compute the relevant values. The model developed in this study is intended for conceptual design and optimization, with parameter values selected from the literature. These parameters directly affect system performance. The influence of receiver temperature on system performance was evaluated through sensitivity analysis. Detailed results are provided in Figure S3 in the Supplementary Materials. The model parameters and their corresponding values are provided in Table 2.

**Table 2.** Process parameter values.

| Parameter                                               | Value                      | Reference |
|---------------------------------------------------------|----------------------------|-----------|
| Direct solar radiation intensity, $DNI$                 | 1029 $\text{W}/\text{m}^2$ | [19]      |
| Optical efficiency, $\eta_{opt}$                        | 75%                        | [19]      |
| Aperture area of each heliostat, $A_{Helio}$            | 121 $\text{m}^2$           | [19]      |
| Receiver aperture area, $A_r$                           | 60 $\text{m}^2$            | [20]      |
| Average surface temperature of the receiver, $T_{surf}$ | 1100 $^{\circ}\text{C}$    | [19,21]   |
| Receiver efficiency, $\varepsilon$                      | 88%                        | [21]      |
| Heating time, $t_{Solar}$                               | 12 h                       | [22]      |
| Wind speed, $V_a$                                       | 3 $\text{m}/\text{s}$      | [23]      |
| HST outlet temperature                                  | 565 $^{\circ}\text{C}$     | [16]      |
| CST outlet temperature                                  | 290 $^{\circ}\text{C}$     | [16]      |
| Number of storage tanks                                 | 2                          | [16]      |

### 2.2.2. ORC Power Generation Subsystem

The ORC consists of four core components: a pump, an evaporator, an expander, and a condenser. R245fa serves as the working fluid. Mass and energy balances are determined using Equations (10) and (11).

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \quad (10)$$

$$\sum \dot{Q} + \sum \dot{E}_{in} = \sum \dot{W} + \sum \dot{E}_{out} \quad (11)$$

where  $\dot{m}_{in}$  and  $\dot{m}_{out}$  denote the mass flow rates entering and exiting the system,  $\text{kg}/\text{s}$ ;  $\dot{E}_{in}$  and  $\dot{E}_{out}$  represent the energy rates entering and exiting the system,  $\text{kJ}/\text{kg}$ ;  $\dot{Q}$  refers to the heat transferred into the system,  $\text{kJ}/\text{s}$ ;  $\dot{W}$  indicates the work output by the system,  $\text{kW}$ .

Based on the isentropic model, expansion power and ORC pump power are determined by Equations (12) and (13), respectively.

$$\dot{W}_{EXP} = \dot{m}_R \cdot (\dot{h}_{05} - \dot{h}_{06}) \cdot \eta_{EXP} \quad (12)$$

$$\dot{W}_{P3} = \dot{m}_R \cdot (\dot{h}_{02} - \dot{h}_{01}) \cdot \eta_{P3} \quad (13)$$

where  $\dot{m}_R$  denotes the mass flow rate of R245fa, kg/s;  $\dot{h}_i$  represents the enthalpy of stream  $i$ , kJ/kg;  $\eta_{EXP}$  stands for the isentropic efficiency of EXP;  $\eta_{P3}$  stands for the mechanical efficiency of pump;  $\dot{W}_{EXP}$  and  $\dot{W}_{P3}$  refer to the power generated by the expander and the power consumed by the pump, respectively, kW.

The power associated with the regenerator (HEX-7), evaporator (HEX-5), and cooler (Cooler-1) can be determined using Equations (14)–(16).

$$\dot{Q}_{HEX-7} = \dot{m}_{06} \cdot (\dot{h}_{06} - \dot{h}_{07}) = \dot{m}_{03} \cdot (\dot{h}_{04} - \dot{h}_{03}) \quad (14)$$

$$\dot{Q}_{HEX-5} = \dot{m}_{04} \cdot (\dot{h}_{05} - \dot{h}_{04}) = \dot{m}_{S6} \cdot (\dot{h}_{S6} - \dot{h}_{S7}) \quad (15)$$

$$\dot{Q}_{Cooler-1} = \dot{m}_{07} \cdot (\dot{h}_{07} - \dot{h}_{01}) \quad (16)$$

The net work output and thermal efficiency of the ORC system are evaluated using Equations (17) and (18) [24].

$$\dot{W}_{NET-ORC} = \dot{W}_{EXP} - \dot{W}_{P3} \quad (17)$$

$$\eta_{ORC} = \frac{\dot{W}_{NET-ORC}}{\dot{Q}_{HEX-5}} \quad (18)$$

### 2.2.3. SRC Power Generation Subsystem

The SRC represents the most widely utilized thermodynamic cycle for power generation. Its primary components are the evaporator, steam turbine, condenser, and circulation pump. To improve the system's thermal efficiency, a regenerator and a low-pressure steam turbine have been incorporated, as proposed by SRC [25].

The power output of the steam turbine ( $\dot{W}_{HPT}$ ) and the power generation efficiency (PGE) of the SRC and ORC systems ( $\eta_{PGE}$ ), excluding balance-of-plant losses and CSP subsystem, are determined using Equations (19) and (20), respectively [16].

$$\dot{W}_{HPT} = \dot{m}_{S1} \cdot (\dot{h}_{S1} - \dot{h}_{S2}) \cdot \eta_{HPT} \quad (19)$$

$$\eta_{PGE} = \frac{\dot{W}_{HPT} + \dot{W}_{LPT} + \dot{W}_{EXP} - \dot{W}_{P2} - \dot{W}_{P3}}{\dot{Q}_{HEX-1} + \dot{Q}_{HEX-2}} \quad (20)$$

The accuracy of the formula for the heat-collection and power-generation system has been established in previous studies [16,23,26]. Validation of the SRC and ORC power generation subsystems was conducted, with simulation results shown in Table S1 in the Supplementary Materials. The relative errors in the simulated thermal efficiency of the power generation system are 3.89% and 2.29%, respectively, which demonstrates the reliability of the models. The power generation module was simulated in Aspen Plus using Equations (10)–(20). Model parameters and their corresponding values are presented in Table 3.

**Table 3.** Process parameter values.

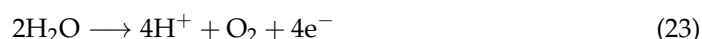
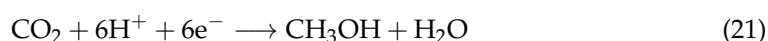
| Parameter                   | Value                |
|-----------------------------|----------------------|
| HPT inlet temperature       | 525 °C               |
| HPT inlet pressure          | $170 \times 10^5$ Pa |
| Circulating steam flow rate | 32.78 kg/s           |
| Efficiency of the turbine   | 0.88                 |
| Cycle fluid                 | R245fa               |
| Efficiency of the expander  | 0.85                 |

Table 3. Cont.

| Parameter              | Value                  |
|------------------------|------------------------|
| EXP inlet temperature  | 110.03 °C              |
| EXP inlet pressure     | $10.10 \times 10^5$ Pa |
| EXP outlet pressure    | $2.85 \times 10^5$ Pa  |
| Circular flow          | 335.16 kg/s            |
| Efficiency of the pump | 0.8                    |

#### 2.2.4. CO<sub>2</sub>RR Subsystem

CO<sub>2</sub>RR remains at the experimental stage due to several limitations, including low current density, limited CO<sub>2</sub> utilization and conversion rates, and low energy conversion efficiency [27]. To address these issues, the present study utilizes a black-box model to simulate the entire reaction process and quantify the correlation between reactant and product quantities. The primary cathodic reaction is the reduction of CO<sub>2</sub> to produce CH<sub>3</sub>OH (Equation (21)), while a competing side reaction produces H<sub>2</sub> (Equation (22)). Simultaneously, the anode undergoes an oxidation reaction to produce O<sub>2</sub> (Equation (23)).



The current required to generate substance *i* is determined using Equation (24). The total current required for the reaction is calculated with Equation (25). The necessary electrical energy is obtained by Equation (26).

$$I_i = n_i F F_{mi} \quad (24)$$

$$I_{\text{total}} = \frac{I_i}{FE_i} \quad (25)$$

$$P = V \cdot I_{\text{total}} \quad (26)$$

where  $I_i$  denotes the current used for generating substance *i*, A;  $n_i$  represents the number of electrons required for reducing CO<sub>2</sub> to generate substance *i*;  $F$  is the Faraday constant, 96,485 C/mol;  $F_{mi}$  refers to the molar flow rate of substance *i*, mol/s;  $I_{\text{total}}$  stands for the total current required for the reaction, A;  $FE_i$  denotes the Faraday efficiency of substance *i*;  $V$  represents the applied potential, V.

The area required for the electrolyzer is determined using Equation (27).

$$AE = \frac{I_{\text{total}}}{j} \cdot \frac{\text{m}^2}{10^4 \text{ cm}^2} \quad (27)$$

where  $j$  denotes the current density, A/cm<sup>2</sup>.

Models corresponding to the aforementioned equations were developed in Fortran within Aspen Plus. The Faradaic efficiency was set at 0.886 for methanol and 0.114 for hydrogen, with the reactor conversion rate serving as an equivalent substitute. The current density was maintained at 0.068 A/cm<sup>2</sup>, the applied potential at 3.2 V, and the methanol production rate at 50 tons/day [28]. Simulation results were compared with theoretical values reported in the literature, as shown in Table 4.

**Table 4.** Comparison of simulated values with theoretical values from the literature.

| Parameter                                  | Analog Value | Theoretical Value [1,8] | Relative Error/% |
|--------------------------------------------|--------------|-------------------------|------------------|
| Feed CO <sub>2</sub> flow rate/(tons/day)  | 67.81        | 68.75                   | 1.37             |
| Feed H <sub>2</sub> O flow rate/(tons/day) | 66.29        | 67.02                   | 1.01             |
| H <sub>2</sub> flow rate/(tons/day)        | 1.18         | 1.20                    | 1.67             |
| CH <sub>3</sub> OH flow rate/(tons/day)    | 47.79        | 50.00                   | 4.42             |
| Tower top temperature/(K)                  | 337.41       | 339.00                  | 0.47             |
| Tower bottom temperature/(K)               | 372.80       | 363.00                  | 2.70             |

The maximum relative error between the model and theoretical values is 4.42%, which demonstrates a high level of consistency. Consequently, the model effectively represents the relationship between substance quantities and changes in distillation process load, making it suitable for analyzing system energy integration.

### 2.3. Energy Integration Analysis

An analysis of the ORC and CO<sub>2</sub>RR modules depicted in Figure 1, along with selected heat exchanger modules (HEX-3, HEX-4, HEX-5) in the SRC, indicates that the process consists of four hot streams and three cold streams. With the minimum temperature difference for heat transfer set at 10 °C, the logistics data of the heat exchange network before and after heat integration are presented sequentially in Table 5, and the corresponding hot and cold composite curves are illustrated in Figure 2. The minimum heat utility (HU) and cool utility (CU) prior to integration (Figure 2a) are 1499.2 kW and 71,191.6 kW, respectively, whereas after integration (Figure 2b), these values are 0 kW and 69,665.2 kW, respectively. The average pinch temperatures, calculated as the arithmetic mean of the hot pinch temperature (PH) and the cold pinch temperature (PC), are 104.7 °C and 109.8 °C, respectively. Following integration, total utility consumption is reduced by 4.2%. Variations in stream temperature influence the system's energy output; the corresponding temperature versus entropy (T-S) diagrams before and after integration are provided in Figure 3. The area enclosed by the graph represents the system's work output. The electrical energy output of the system before integration (Figure 3a) is 46,304.8 kW, and after integration (Figure 3b) is 46,345.4 kW, indicating a 0.08% increase in total power generation.

**Table 5.** Stream data of the integrated pre- and post-HEN.

| Stream | Heat Exchanger      | Inlet Temperature/°C | Outlet Temperature/°C | Heat Capacity Flow Rate/(kW·°C <sup>-1</sup> ) |
|--------|---------------------|----------------------|-----------------------|------------------------------------------------|
| H1     | HEX-3, HEX-4, HEX-5 | 152.1/152.1          | 109.4/109.4           | 1778.5/1778.5                                  |
| H2     | HEX-6               | 64.3/64.3            | 64.2/64.2             | 23,333.7/23,333.7                              |
| H3     | HEX-7, Cooler-1     | 75.82/72.85          | 30.3/30.3             | 1299.4/1562.6                                  |
| H4     | Cooler-2            | 97.2/97.2            | 25.0/25.0             | 3.2/3.2                                        |
| C1     | HEX-3               | 114.4/114.4          | 125.3/125.3           | 155.2/155.2                                    |
| C2     | HEX-4               | 91.9/91.9            | 97.2/97.2             | 284.7/284.7                                    |
| C3     | HEX-5, HEX-6, HEX-7 | 30.3/30.3            | 112.3/97.3            | 1127.7/1304.3                                  |

The results of the Energy Integration Analysis indicate that, assuming total power generation remains constant, heat integration among the SRC, ORC, and CO<sub>2</sub>RR subsystems leads to reduced utility consumption.

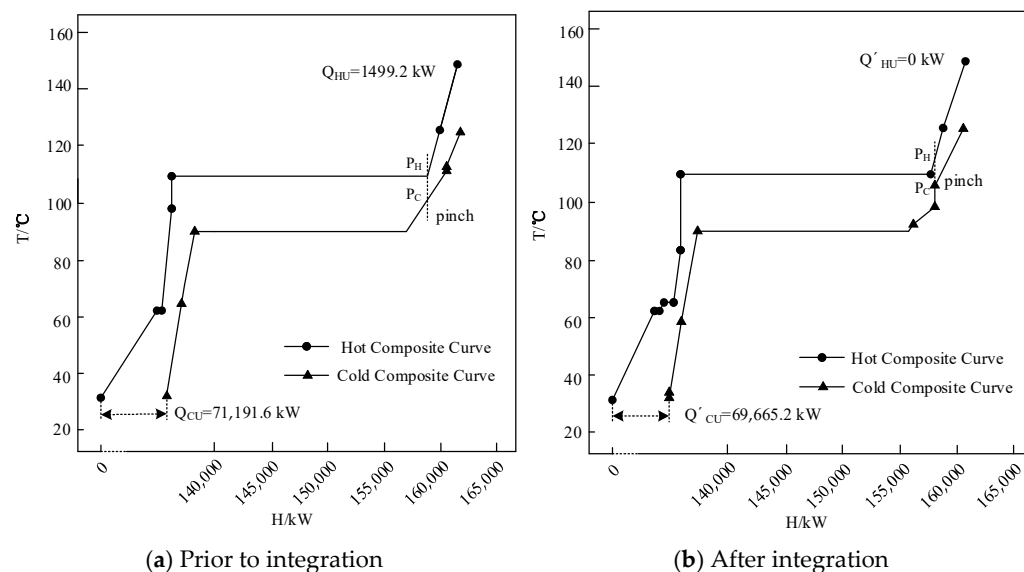


Figure 2. Composite curves of the system prior to and after integration.

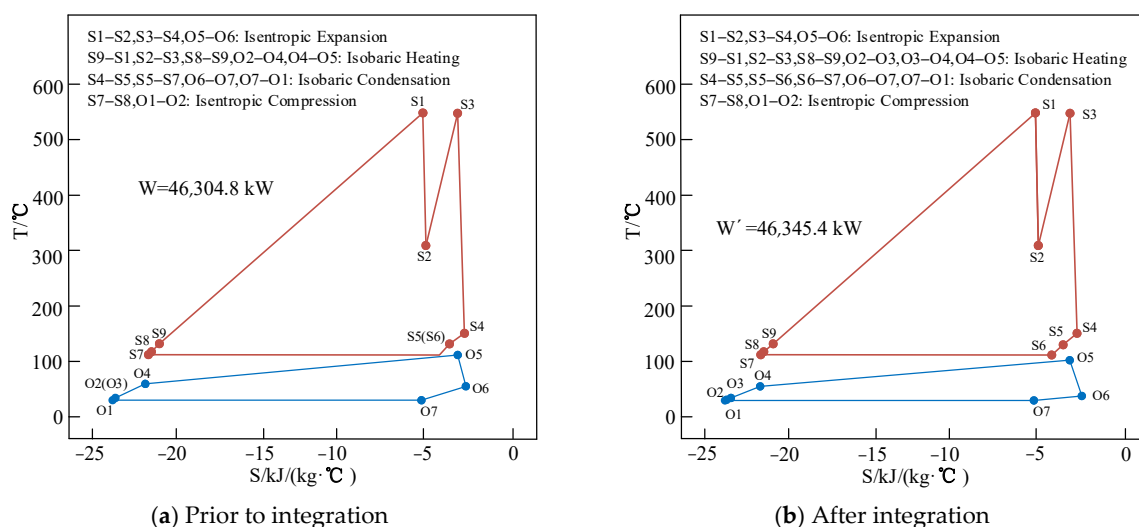


Figure 3. Temperature-entropy diagrams of the system prior to and after integration.

### 3. System Performance Evaluation

#### 3.1. Economic Analysis

##### 3.1.1. Total Production Cost (TPC)

The total production cost (TPC) comprises the annual capital cost (ACC) and the total operating cost (TOC), and is determined using Equation (28) [19,29,30].

$$\text{TPC} = \text{ACC} + \text{TOC} = \sum Z_k \times \zeta \times \text{CRF} + 350 \times \dot{C}_{\text{CO}_2} \times m_{\text{CO}_2} + 350 \times \dot{C}_{\text{H}_2\text{O}} \times m_{\text{H}_2\text{O}} \quad (28)$$

where  $\sum Z_k$  denotes the total cost of the system equipment;  $\zeta$  denotes the operation and maintenance coefficient; CRF refers to the capital recovery factor;  $\dot{C}_{\text{CO}_2}$  represents the cost of carbon capture, USD/ton;  $\dot{C}_{\text{H}_2\text{O}}$  refers to the cost of  $\text{H}_2\text{O}$ , USD/ton;  $\dot{m}_{\text{CO}_2}$  and  $\dot{m}_{\text{H}_2\text{O}}$  denote the mass flow rates of the feed carbon dioxide and water, tons/day.

The cost calculation formulas for each piece of equipment in the system are presented in Table S1 in the Supplementary Materials, and can be adjusted using Equation (29) [23]. At present, industrial-scale  $\text{CO}_2\text{RR}$  electrolysis equipment is not available. Consequently,

the cost of the electrolyzer was calculated using alkaline-water electrolyzer cells from the U.S. Department of Energy [30].

$$Z_k = Z_k^0 \times \frac{CEPCI}{CEPCI^0} \quad (29)$$

where  $CEPCI$  denotes the chemical engineering plant cost index of the current year, while  $CEPCI^0$  refers to the index for the reference year.

The CRF calculation formula is provided in Equation (30) and depends on the interest rate and the equipment's service life.

$$CRF = \frac{i(1+i)^L}{(1+i)^L - 1} \quad (30)$$

where  $L$  represents the project's lifetime and  $i$  denotes the interest rate.

Since the distillation column's operating power is supplied by waste heat from the power generation system, the operating cost associated with this distillation column is zero.

### 3.1.2. Levelized Cost of Methanol (LCOM)

The Levelized Cost of Methanol (LCOM) serves as a key metric for evaluating and comparing methanol production systems. Its calculation formula is presented in Equation (31) [2,8,23].

$$LCOM = \frac{TPC \times \frac{10^6 \$}{1M\$} - 350 \times \dot{W}_{Net,day} \times \dot{C}_{elec} \times \frac{10^3 kWh}{1MWh} - 350 \times \dot{C}_{O_2} \times \dot{m}_{O_2}}{350 \times \dot{m}_{CH_3OH} \times \frac{10^3 kg}{1ton}} \quad (31)$$

where  $\dot{W}_{Net,day}$  denotes the grid-connected electrical energy, MWh/day;  $\dot{C}_{elec}$  represents the system power generation price, USD/kWh;  $\dot{C}_{O_2}$  refers to the price of  $O_2$ , USD/ton.

The value of  $\dot{W}_{Net,day}$  is calculated using Equation (32).

$$\dot{W}_{Net,day} = 24(\dot{W}_{HPT} + \dot{W}_{LPT} + \dot{W}_{EXP} - P - \dot{W}_{P2} - \dot{W}_{P3} - \dot{W}_{PSA} - \dot{W}_{BOP}) - t_{Solar} \dot{W}_{P1} \quad (32)$$

where  $\dot{W}_{BOP}$  denotes the plant energy demand, which is assumed to constitute 10% of the energy required for the carbon dioxide reduction reaction [8].

Table 6 presents the parameters used for economic analysis. The operation and maintenance coefficients for the heat collection and power generation system and the reaction and separation system are provided sequentially.

**Table 6.** Parameters used for economic analysis.

| Parameter                                      | Value        | Reference |
|------------------------------------------------|--------------|-----------|
| Reference Year                                 | 2022         | /         |
| $CEPCI$                                        | 832.6        | [24]      |
| Interest Rate, $i$                             | 10%          | [8]       |
| Project Life, $L$                              | 20yr         | [8]       |
| Operation and Maintenance Coefficient, $\zeta$ | 1.06/1.025   | [23,30]   |
| $CO_2$ Capture Cost, $\dot{C}_{O_2}$           | USD 40/ton   | [1,8]     |
| $H_2O$ Cost, $\dot{C}_{O_2}$                   | USD 0.5/ton  | [13]      |
| Electricity Price, $\dot{C}_{elec}$            | USD 0.22/kWh | [27]      |
| $O_2$ Price, $\dot{C}_{O_2}$                   | USD 50/ton   | [1]       |

### 3.2. Environmental Analysis

In accordance with the ISO 14040/14044 standard framework, the system was evaluated across its entire life cycle [8]. The system boundary for life cycle assessment (LCA) is illustrated in Figure 4.

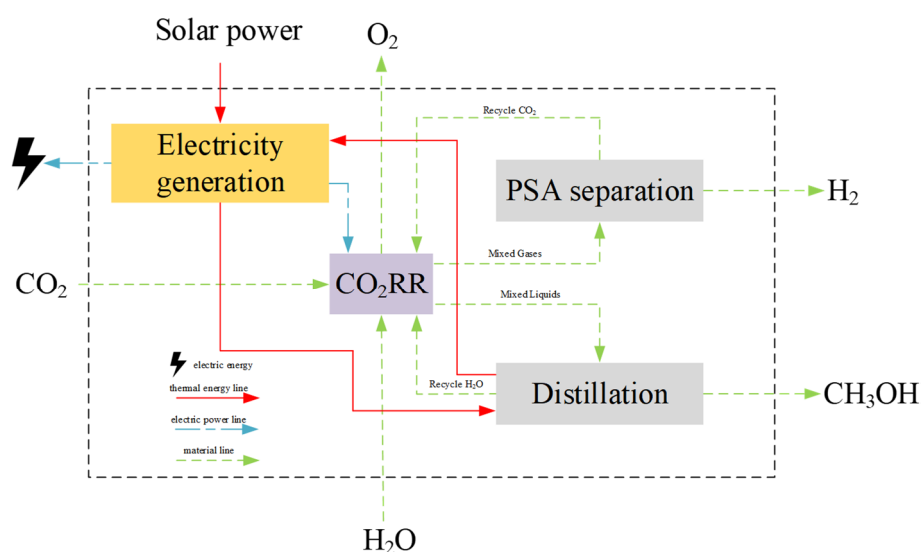


**Figure 4.** System boundary for life cycle assessment (LCA).

In this study, the carbon footprint of feed CO<sub>2</sub> is assumed to be −0.5 kg CO<sub>2</sub> per 1 kg CO<sub>2</sub> consumed [8]. Consequently, the specific carbon emission (SCE) of CO<sub>2</sub> is calculated using Equation (33).

$$CO_{2SCE} = -0.5 \frac{\text{kg } CO_2e}{\text{kg} - \text{consumed } CO_2} \times \frac{m_{CO_2}}{m_{CH_3OH}} \quad (33)$$

where  $m_i$  denotes the mass flow rate of substance  $i$ , tons/day.

The carbon emission factor for the water treatment process is 0.78 kWh/ton H<sub>2</sub>O [31]. The carbon footprint factor for solar thermal power generation is 0.0227 kgCO<sub>2</sub>e/kWh [32]. Carbon emissions from upstream processes associated with equipment manufacturing are also included in the electricity-related CO<sub>2</sub> emission factor. Therefore, the carbon intensity of water is calculated using Equation (34).

$$H_2O_{SCE} = 0.0227 \frac{\text{kg } CO_2e}{\text{kWh}} \times 0.78 \frac{\text{kWh}}{\text{ton}} \times \frac{1 \text{ ton}}{1000 \text{ kg}} \times \frac{m_{H_2O}}{m_{CH_3OH}} \quad (34)$$

The standard energy consumption values are 200 kWh/ton for O<sub>2</sub> and 50 kWh/ton for H<sub>2</sub> [8], respectively. In 2022, the CO<sub>2</sub> emission intensity of power generation in Northwest China was 0.65 kg CO<sub>2</sub>e/kWh [33]. Equations (35) and (36) are used to calculate the environmental burden associated with O<sub>2</sub> and H<sub>2</sub>.

$$O_{2burden} = 0.65 \frac{\text{kg } CO_2e}{\text{kWh}} \times 200 \frac{\text{kWh}}{\text{ton } O_2} \times \frac{1 \text{ ton}}{1000 \text{ kg}} \times \frac{m_{O_2}}{m_{CH_3OH}} \quad (35)$$

$$H_{2burden} = 0.65 \frac{\text{kg } CO_2e}{\text{kWh}} \times 50 \frac{\text{kWh}}{\text{kg } H_2} \times \frac{m_{H_2}}{m_{CH_3OH}} \quad (36)$$

A portion of the electrical energy generated by the system is allocated to CO<sub>2</sub>RR, while the remainder is used for output power (OP). The pressure swing adsorption (PSA) separa-

tion device requires 0.25 kWh/m<sup>3</sup> for specific treatment energy consumption. Accordingly, the relevant calculation formulas are presented in Equations (37)–(40).

$$OP_{SCE} = 0.0227 \frac{\text{kg CO}_2\text{e}}{\text{kWh}} \times \frac{\dot{W}_{\text{Net,day}}}{m_{\text{CH}_3\text{OH}}} \quad (37)$$

$$\text{CO}_2\text{RR}_{SCE} = 0.0227 \frac{\text{kg CO}_2\text{e}}{\text{kWh}} \times \frac{P}{m_{\text{CH}_3\text{OH}}} \times \frac{24 \text{ h}}{1 \text{ day}} \quad (38)$$

$$\text{PSA}_{SCE} = 0.0227 \frac{\text{kg CO}_2\text{e}}{\text{kWh}} \times 0.25 \frac{\text{kWh}}{\text{m}^3} \times \frac{V_m}{m_{\text{CH}_3\text{OH}}} \times \frac{24 \text{ h}}{1 \text{ day}} \quad (39)$$

$$\text{BoP}_{SCE} = 0.0227 \frac{\text{kg CO}_2\text{e}}{\text{kWh}} \times \frac{0.1P}{m_{\text{CH}_3\text{OH}}} \times \frac{24 \text{ h}}{1 \text{ day}} \quad (40)$$

The net specific carbon emission (Net<sub>SCE</sub>) for the entire system is calculated according to Equation (41).

$$\text{Net}_{SCE} = \text{CO}_{2SCE} + \text{H}_2\text{O}_{SCE} - \text{O}_{2\text{burden}} - \text{H}_{2\text{burden}} + \text{OP}_{SCE} + \text{CO}_2\text{RR}_{SCE} + \text{PSA}_{SCE} + \text{BoP}_{SCE} \quad (41)$$

### 3.3. Energy Efficiency Analysis

The energy efficiency ( $\eta_{\text{en}}$ ) of the system is calculated using Equation (42).

$$\eta_{\text{en}} = \frac{24\dot{m}_{\text{CH}_3\text{OH}}\text{LHV}_{\text{CH}_3\text{OH}} + \dot{W}_{\text{Net,day}}}{t_{\text{Solar}}\dot{Q}_{\text{Solar}}} \quad (42)$$

where  $\text{LHV}_{\text{CH}_3\text{OH}}$  denotes the lower heating value of methanol, which is 15.8 MJ/kg.

### 3.4. Evaluation Results

The results of the system simulation are presented in Table 7. The system's energy efficiency is 6.70%, which is significantly lower than the reference theoretical value of 14% [12]. This discrepancy arises because previous studies have focused solely on the direct conversion of electrical energy into chemical energy. In contrast, as indicated by Equation (42), the present study includes an additional step in which solar thermal energy is first converted into electrical energy. This multistage energy conversion process is the primary reason for the observed difference.

**Table 7.** Simulation Results.

| Parameter                                                   | Value                                              |
|-------------------------------------------------------------|----------------------------------------------------|
| Product                                                     |                                                    |
| CH <sub>3</sub> OH                                          | 47.79 tons/day                                     |
| H <sub>2</sub>                                              | 1.18 tons/day                                      |
| O <sub>2</sub>                                              | 82.84 tons/day                                     |
| Power ( $\dot{W}_{\text{Net,day}}$ )                        | 121.80 MWh/day                                     |
| Assessment result                                           |                                                    |
| Total Production Cost (TPC)                                 | USD 55.8 M/year                                    |
| Net specific CO <sub>2</sub> emission (Net <sub>SCE</sub> ) | −1.12 kg CO <sub>2SCE</sub> /kg CH <sub>3</sub> OH |
| Energy efficiency ( $\eta_{\text{EN}}$ )                    | 6.70%                                              |
| Power generation efficiency ( $\eta_{\text{PGE}}$ )         | 40.67%                                             |
| Levelized cost of methanol (LCOM)                           | USD 2.69/kg                                        |
| Number of fixed mirrors (N)                                 | 13,311                                             |
| The height of the heat collection tower (H <sub>t</sub> )   | 246.64 m                                           |

## 4. Parameter Analysis and Multiobjective Optimization

### 4.1. Parameter Analysis

Figure 5 illustrates the effect of EXP outlet pressure on system performance. As the outlet pressure rises, the system's LCOM and  $Net_{SCE}$  rise, whereas  $\eta_{EN}$ ,  $\eta_{PGE}$ , and  $W_{Net,day}$  decline. Therefore, raising the expander's outlet pressure enhances environmental benefits but diminishes economic performance and energy efficiency.

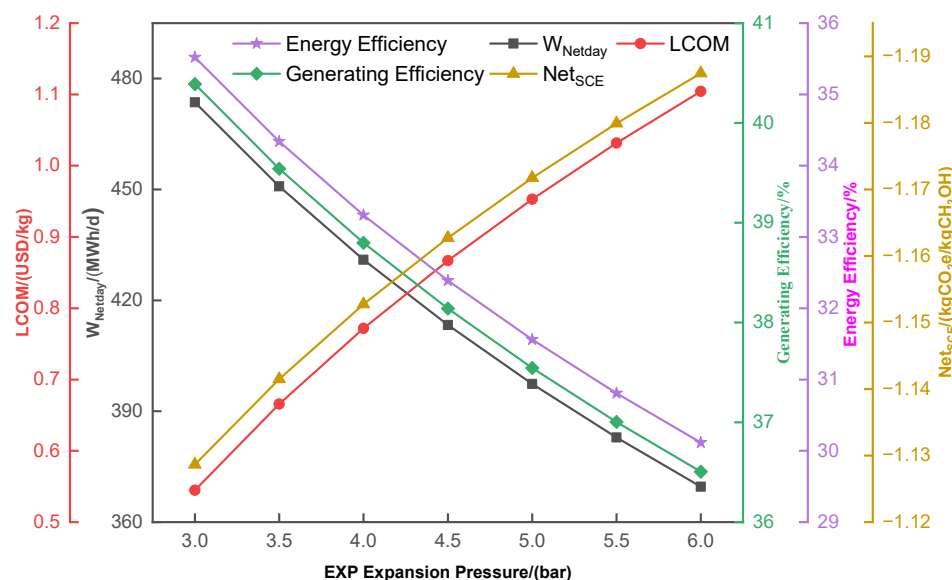


Figure 5. The influence of EXP outlet pressure on system performance.

Figure 6 presents the influence of the evaporator (HEX-5) cold-fluid outlet temperature on system performance. As the cold fluid outlet temperature increases, the values of  $\eta_{EN}$ ,  $\eta_{PGE}$ ,  $Net_{SCE}$ , and  $W_{Net,day}$  all increase, while LCOM decreases. Thus, elevating the cold-fluid outlet temperature of the evaporator improves economic performance and energy efficiency but reduces environmental benefits.

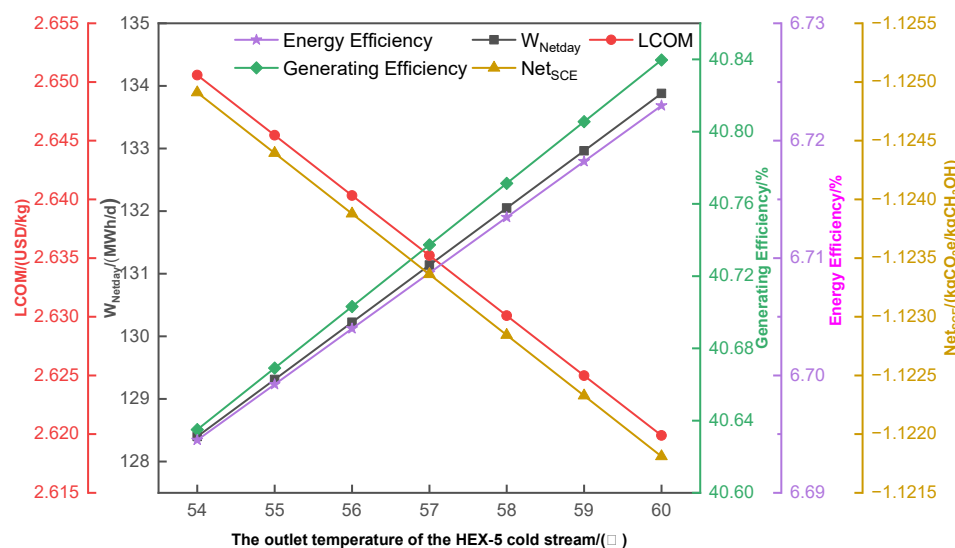


Figure 6. The influence of HEX-5 outlet temperature on system performance.

Figure 7 presents the effect of feed rate on the system, with proportional increases in the mass flow rates of CO<sub>2</sub> and H<sub>2</sub>O. As the feed rate increases, methanol production and

LCOM increase. However,  $\eta_{EN}$ ,  $\dot{W}_{Net,day}$ , and  $Net_{SCE}$  all decline. Therefore, while reducing the feed rate improves economic performance, it adversely affects both energy efficiency and environmental outcomes.

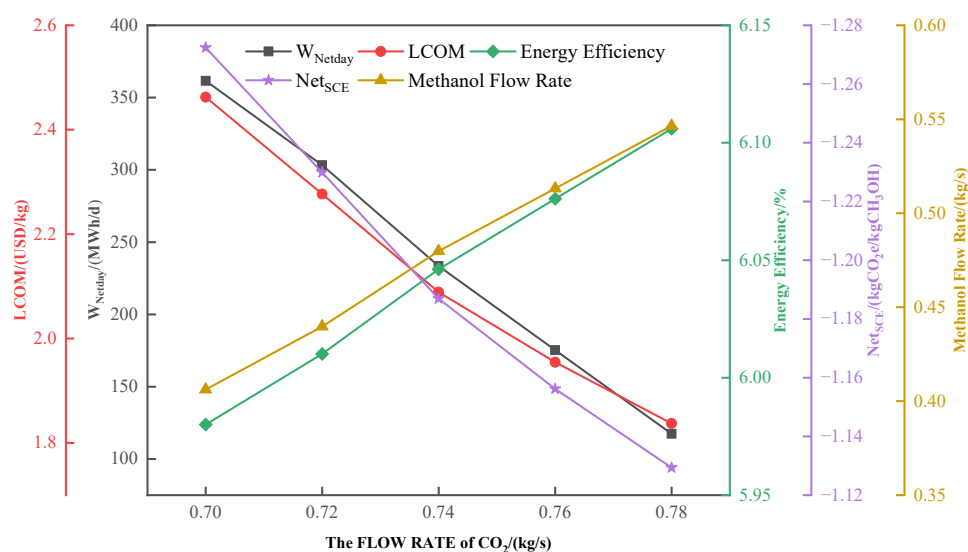


**Figure 7.** The influence of feed rate on system performance.

Current density and applied potential are critical parameters influencing the economic feasibility of the system. Figure 8 demonstrates that  $\dot{W}_{Net,day}$  increases as the applied potential decreases. Conversely, LCOM decreases with increasing current density and decreasing applied potential, exhibiting greater sensitivity to applied potential. The reason is that current density primarily affects the stack cost of the electrolyzer, while applied potential determines energy input, with electricity constituting the dominant component of operating costs. The industrial reference values for current density and applied potential in CO<sub>2</sub>RR are 0.4 A/cm<sup>2</sup> and 2.2 V, respectively [12,34]. To enable direct comparison with other processes, these reference values are adopted for current density and voltage in the multiobjective optimization. The initial results are shown in Table 8.

**Table 8.** The initial results for multiobjective optimization.

| Parameter                                                                      | Value  |
|--------------------------------------------------------------------------------|--------|
| LCOM/(USD/kg)                                                                  | 0.886  |
| Net <sub>SCE</sub> /(kg CO <sub>2</sub> <sub>SCE</sub> /kg CH <sub>3</sub> OH) | −1.20  |
| $\eta_{EN}$ /%                                                                 | 6.16   |
| $\dot{W}_{Net,day}$ /(MWh/day)                                                 | 410.42 |

For the entire system,  $\eta_{EN}$  and  $\dot{W}_{Net,day}$  should be maximized, while LCOM and  $Net_{SCE}$  should be minimized. Figures 5 and 6 indicate that decreasing the outlet pressure of EXP and increasing the outlet temperature of the evaporator (HEX-5) resulting in optimal values for  $\eta_{EN}$ ,  $\dot{W}_{Net,day}$ , and LCOM, whereas  $Net_{SCE}$  becomes suboptimal. As illustrated in Figure 7, increasing the feed flow rate leads to optimal  $\eta_{EN}$  and LCOM, while  $\dot{W}_{Net,day}$  and  $Net_{SCE}$  become suboptimal. Therefore, multiobjective optimization is employed to identify the optimal operating parameters for the system.

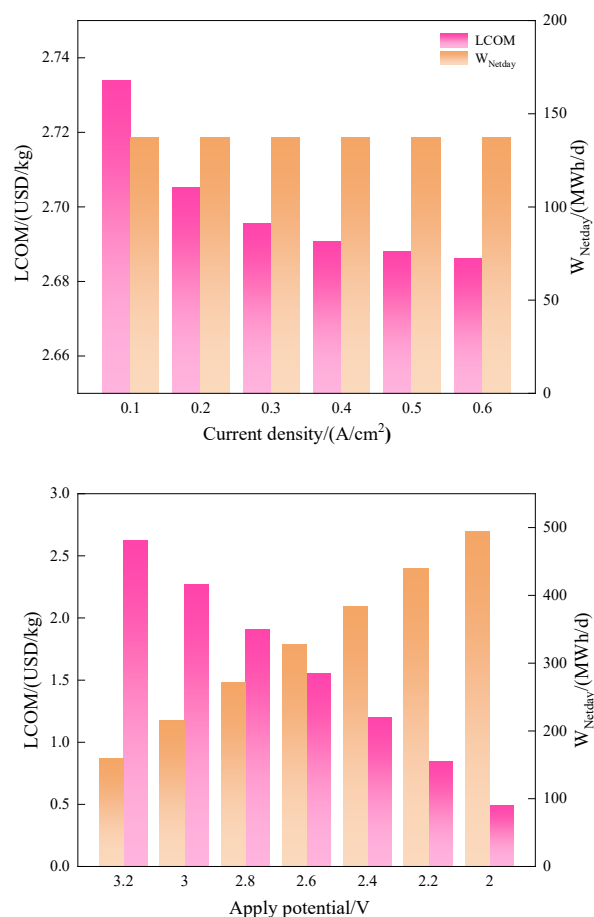


**Figure 8.** The influence of electrochemical parameters on the system.

#### 4.2. Multiobjective Optimization

The optimization objectives of this study are to minimize LCOM and maximize  $\eta_{EN}$  and  $Net_{SCE}$ , as defined in Equations (43) and (44).

$$Find \min func = \{LCOM, Net_{SCE}\} \quad (43)$$

$$Find \max func = \{\eta_{EN}\} \quad (44)$$

NSGA-II is a widely used multiobjective optimization algorithm that integrates non-dominated sorting, crowding distance, and elite selection strategies to identify the Pareto-optimal solution set. In this study, the objective function evaluation model was developed in Fortran within Aspen Plus V12, while the NSGA-II algorithm was implemented in MATLAB R2024b. The parameter settings are detailed in Table 9. Software interaction was facilitated through the Component Object Model (COM), which enabled the transfer of Aspen Plus results to MATLAB and allowed feedback to inform subsequent Aspen Plus simulations. The non-dominated Pareto solutions were standardized using Equation (45), and Equation (46) was applied to compute the Euclidean distance ( $ED_{i+}$ ) between each point on the Pareto frontier and the ideal point. Figure 9 illustrates the multiobjective optimization process. Non-convergent solutions were systematically excluded by monitoring convergence status in Aspen Plus, and the final set of convergent solutions is summarized in Table S3 of the Supplementary Materials.

$$f_{ij}^{norm} = \frac{f_{ij} - \min(f_{ij})}{\max(f_{ij}) - \min(f_{ij})} \quad (45)$$

$$ED_{i+} = \sqrt{\sum_{j=1}^n (f_{ij}^{norm} - f_{ij}^{ideal})^2} \quad (46)$$

**Table 9.** Parameter values related to NSGA-II.

| Parameter                    | Value |
|------------------------------|-------|
| Population Size              | 70    |
| Maximum Number of Iterations | 70    |
| Crossover Probability        | 0.8   |
| Mutation Probability         | 1/7   |
| Crossover Distribution Index | 15    |
| Mutation Distribution Index  | 20    |

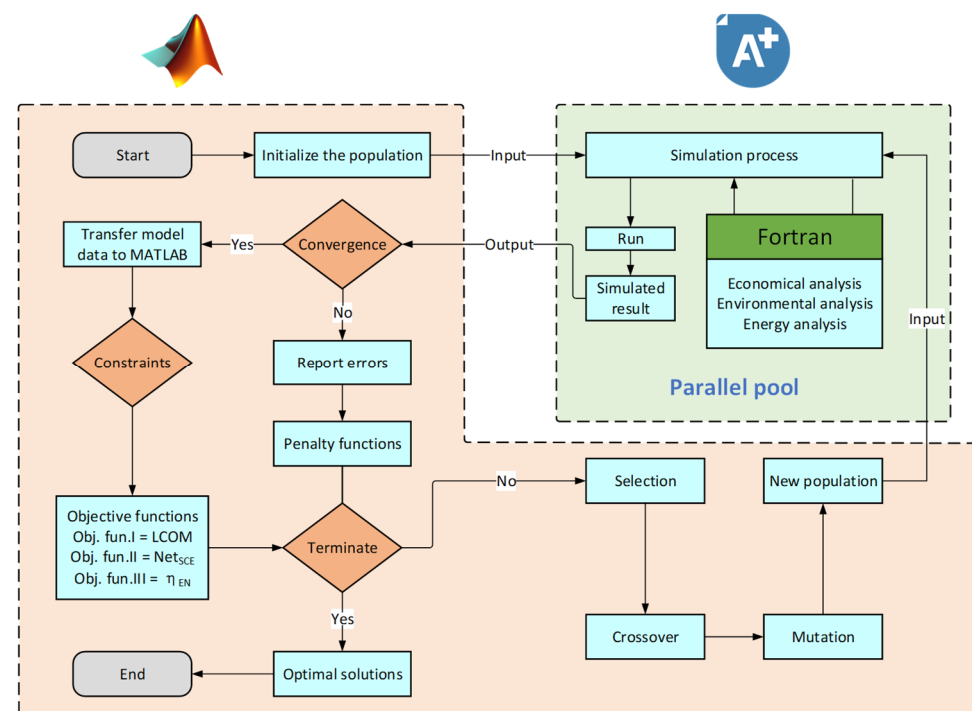
**Figure 9.** The optimization procedure with NSGA-II.

Figure 10 presents the Pareto frontier solution set, comprising 17 feasible solutions. The corresponding values are provided in Table S3 in the Supplementary Materials. The unweighted solution is indicated, selected according to spatial geometry. Table 10 details the value ranges for the optimization process variables and constraint conditions.

Each solution on the Pareto frontier imposes constraints on the others, preventing simultaneous optimality. Consequently, evaluating and screening the solution set is essential. Selection methods based on spatial geometry or entropy-weight TOPSIS (technique for order preference by similarity to ideal solution) may introduce subjective biases or distort objective indices. The analytic hierarchy process (AHP) is a multicriteria decision analysis method that integrates subjective judgments with objective data within a unified analytical framework. Therefore, the combined AHP-TOPSIS method is adopted to screen the Pareto frontier solution set. The calculation steps are provided in Equations (S1)–(S15) in the Supplementary Materials.

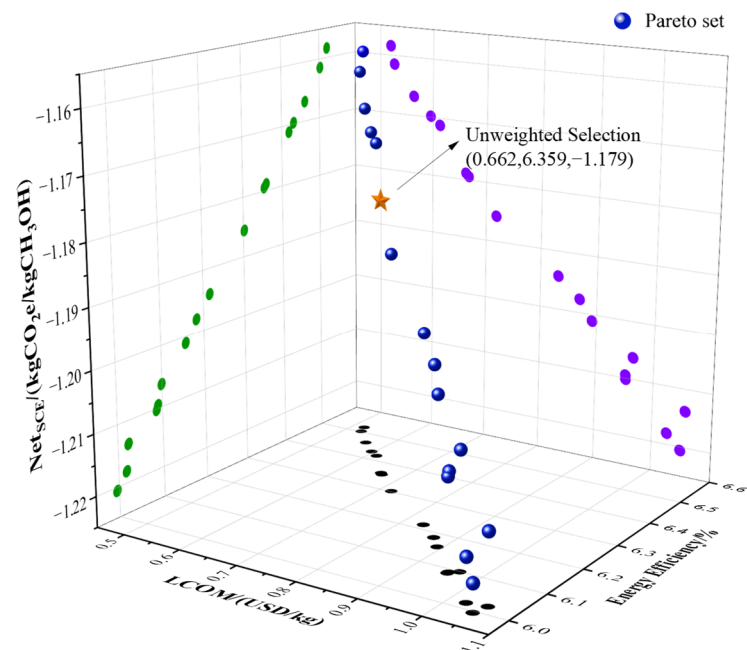


Figure 10. The Pareto frontier solution set.

Table 10. The value ranges for the optimization process variables and constraint conditions.

| Variables and Constraints                         | Value Range                        | Unit               |
|---------------------------------------------------|------------------------------------|--------------------|
| Variables                                         |                                    |                    |
| CO <sub>2</sub> feed rate                         | 0.70–0.78                          | kg/s               |
| HPT outlet pressure                               | 28–40                              | 10 <sup>5</sup> Pa |
| LPT outlet pressure                               | 1.25–1.50                          | 10 <sup>5</sup> Pa |
| EXP outlet pressure                               | 2.8–6                              | 10 <sup>5</sup> Pa |
| HEX-5 outlet temperature                          | 52–60                              | °C                 |
| Total number of stages of the distillation column | 20–30                              | /                  |
| Feed stage number of the distillation column      | 9–24                               | /                  |
| Constraints                                       |                                    |                    |
| Pump P1 head                                      | $H_{P100} > H_t$                   | m                  |
| Temperature of streams G7 and G9                  | $T_{G7} \geq 293, T_{G9} \geq 293$ | °C                 |
| $\dot{W}_{Net,day}$                               | $\dot{W}_{Net,day} \geq 0$         | MWh/day            |
| Mass fraction of methanol in stream R11           | $w_{tCH4O} \geq 0.995$             | /                  |

In this study,  $m$  is set to 17 and  $n$  to 3. The subjective judgment matrix is constructed using the 1–9 scale method [35]. Currently, no investigation or expert consensus has established the precise scale of the objective function for this context. Consequently, the subjectively constructed judgment matrix, informed by related literature, is presented in Equation (47) [36]. The calculated weights for LCOM, Net<sub>SCE</sub>, and  $\eta_{EN}$  are 0.54, 0.3, and 0.16, respectively. The Consistency Ratio (C.R.) is 0.008, indicating that the judgment matrix is reasonable. Figure 11 illustrates the final evaluation ranking of all solutions. According to the AHP-TOPSIS method, the 16th group of Pareto solutions yields the minimum  $C_i$  value, with corresponding LCOM, Net<sub>SCE</sub>, and  $\eta_{EN}$  values of USD 0.526/kg, −1.16 kg CO<sub>2SCE</sub>/kg

CH<sub>3</sub>OH, and 6.50%, respectively. Under these operating conditions, the production capacity of CH<sub>3</sub>OH and  $\dot{W}_{\text{Net,day}}$  are 45.27 tons/day and 475.83 MWh/day, respectively.

$$Y = \begin{bmatrix} 1 & 2 & 3 \\ 1/2 & 1 & 2 \\ 1/3 & 1/2 & 1 \end{bmatrix} \quad (47)$$

where  $i = 1, 2, 3$  correspond to the indicators LCOM, Net<sub>SCE</sub>, and  $\eta_{\text{EN}}$ , respectively.

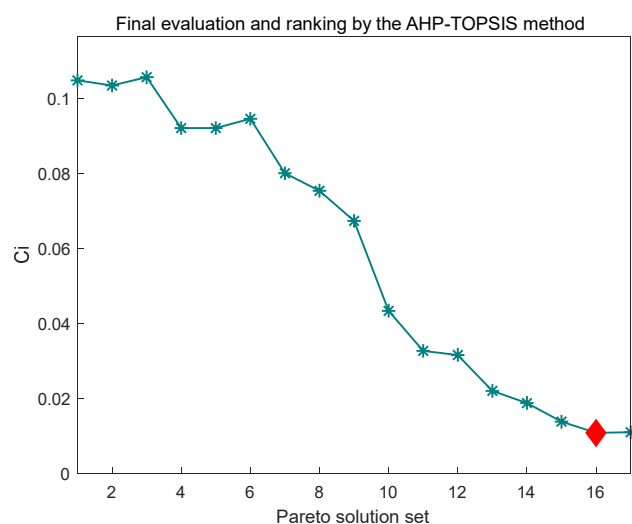


**Figure 11.** The evaluation ranking of all Pareto solutions.

#### 4.3. Optimization Results Analysis and Discussion

Analysis of Equations (33) and (44) indicates that LCOM is correlated with  $\dot{W}_{\text{Net,day}}$ , while  $\eta_{\text{EN}}$  is correlated with both  $\dot{W}_{\text{Net,day}}$  and  $\dot{m}_{\text{CH}_3\text{OH}}$ . Additionally,  $\dot{W}_{\text{Net,day}}$  is inversely proportional to  $\eta_{\text{EN}}$ . The observed increase in  $\eta_{\text{EN}}$  with rising  $\dot{W}_{\text{Net,day}}$  indicates that the energy efficiency of the system's power generation process surpasses that of the electrochemical reaction production process. However, the electrochemical process provides greater environmental benefits, and consequently, resulting in a corresponding increase in Net<sub>SCE</sub>.

Figures S4 and S5 in the Supplementary Materials present the sample results and optimal solutions obtained under varying algorithm parameters [37,38]. The data demonstrate that the samples stabilize and the optimal solutions remain consistent after 70 iterations.

Table 11 compares the selected solutions for weighted and unweighted cases. Assigning a higher weight to LCOM results in a 20.5% decrease, indicating improved economic performance. In this scenario,  $\eta_{\text{EN}}$  increases by 2.53%, while Net<sub>SCE</sub> decreases by 1.61%.

**Table 11.** Comparison of selected solutions for weighted and unweighted cases.

| Optimization Objectives                                            | Unweighted Solution | Weighted Solution | Relative Increment |
|--------------------------------------------------------------------|---------------------|-------------------|--------------------|
| LCOM/(USD/kg)                                                      | 0.662               | 0.526             | +20.5%             |
| Net <sub>SCE</sub> /(kg CO <sub>2SCE</sub> /kg CH <sub>3</sub> OH) | −1.179              | −1.16             | −1.61%             |
| $\eta_{\text{EN}}/\%$                                              | 6.359               | 6.52              | +2.53%             |

Table 12 presents a comparison of results before and after optimization. Following optimization, LCOM is significantly reduced, while  $\eta_{\text{EN}}$  and Net<sub>SCE</sub> exhibit moderate

increases. This outcome arises because economic feasibility remains the primary constraint for CO<sub>2</sub>RR, leading to a higher LCOM weight in the AHP.

**Table 12.** Comparison of system performance before and after optimization.

| Optimization Objectives                                            | Before Optimization | After Optimization | Relative Increment |
|--------------------------------------------------------------------|---------------------|--------------------|--------------------|
| LCOM/(USD/kg)                                                      | 0.886               | 0.526              | +40.6%             |
| Net <sub>SCE</sub> /(kg CO <sub>2SCE</sub> /kg CH <sub>3</sub> OH) | −1.20               | −1.16              | −3.44%             |
| η <sub>EN</sub> /%                                                 | 6.16                | 6.52               | +5.84%             |

Currently, research on CO<sub>2</sub>RR integrated systems is primarily limited to conceptual system design, while investigations into CO<sub>2</sub>RR reaction electrolysis remain at the experimental stage. Table 13 presents a comparative analysis of LCOM and Net<sub>SCE</sub> for the proposed system and for CO<sub>2</sub>RR-based methanol production systems reported in the literature from 2022 to 2025. The results indicate that the LCOM of the proposed system exceeds the values reported in the literature (the market price of green methanol is USD 0.5/kg), whereas the Net<sub>SCE</sub> is substantially lower than previously reported values. This outcome is attributed to the high leveled cost of electricity associated with solar thermal power generation, which is offset by its low carbon-emission factor, thereby providing significant environmental benefits. Although the optimized system demonstrates improved performance, it does not yet achieve the commercial viability threshold. Currently, no commercialized hybrid system combining CSP and CO<sub>2</sub>RR for methanol production exists. The principal barrier is the elevated cost of power supply. A sensitivity analysis of the electricity selling price ( $\dot{C}_{elec}$ ), presented in Figure S2 in the Supplementary Materials, indicates that the system attains commercial viability when  $\dot{C}_{elec}$  exceeds USD 0.223/kWh.

**Table 13.** Comparison between this study and other methods.

| Reference | LCOM/(USD/kg) | Ratio  | Net <sub>SCE</sub> /(kg CO <sub>2SCE</sub> /kg CH <sub>3</sub> OH) | Relative Ratio | Scale/(tons/day) |
|-----------|---------------|--------|--------------------------------------------------------------------|----------------|------------------|
| [8]       | 0.197         | −62.1% | 5.552                                                              | +578.6%        | 50               |
| [1]       | 0.435         | −16.3% | −0.534                                                             | +54.0%         | 1100             |
| [13]      | 0.452         | −13.1% | /                                                                  | /              | 1525             |

## 5. Conclusions

This study proposed a solar-electric-green methanol polygeneration integrated system consisting of a solar heat collection system, a Steam Rankine Cycle (SRC) power generation system, an Organic Rankine Cycle (ORC) power generation system, and a CO<sub>2</sub>RR and separation system. A 3E evaluation, encompassing economic, environmental, and energy-efficiency metrics, was conducted for the proposed system. Multiobjective optimization using the Non-dominated sorting genetic algorithm-II (NSGA-II) and the integration of Aspen Plus V12 with MATLAB R2024b yields a non-dominated Pareto solution set. The technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method framework, based on the Analytic Hierarchy Process (AHP), can screen the solution set and determine the optimal solution. Energy integration analysis revealed that total utility consumption can be reduced by 4.2% without significant changes in power generation. The Pareto optimal values for LCOM, Net<sub>SCE</sub>, and η<sub>EN</sub> for the proposed system are 0.526 USD/kg, −1.16 kg CO<sub>2SCE</sub>/kg CH<sub>3</sub>OH, and 6.50%, respectively. Relative to the pre-optimization results, LCOM decreases by 40.6%, while Net<sub>SCE</sub> and η<sub>EN</sub> rise by 3.44% and 5.84%, respectively. Under the corresponding operating conditions, the production capacity of CH<sub>3</sub>OH and  $\dot{W}_{Net,day}$  are 45.27 tons/day and 475.83 MWh/day, respectively. Despite optimization, the

system does not meet the commercial threshold. The optimized system still fails to meet the commercial threshold. The results indicate commercial viability is achieved when the electricity selling price exceeds USD 0.223/kWh.

The proposed system has the potential to reduce the production cost of green methanol through the Carbon Dioxide Reduction Reaction (CO<sub>2</sub>RR) by integrating energy and introducing a novel selection method for solution sets in multiobjective system optimization. However, the coupled system developed for CO<sub>2</sub>RR in this study analyzes the effects of individual electrochemical parameters, without accounting for kinetic relationships among parameters, the dimensions and scale of the electrolyzer stacks, energy volatility, or catalyst effects. The environmental analysis relies on the net specific carbon emission (Net<sub>sCE</sub>) to represent environmental benefits, without providing a comprehensive assessment of the role and magnitude of assumed carbon credits. Future research will address these limitations by exploring the system's response mechanisms in diverse application scenarios, enhancing optimization algorithms, modeling electrochemical reaction kinetics, advancing electrolyzer development, analyzing scale consistency, and establishing a more comprehensive framework for carbon credits analysis.

**Supplementary Materials:** The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/pr14030508/s1>.

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## Nomenclature and Abbreviations

### Nomenclature

|            |                                               |
|------------|-----------------------------------------------|
| $A$        | Area, m <sup>2</sup>                          |
| $A_E$      | Required area of the electrolyzer             |
| $C_{elec}$ | System power generation price, USD/kWh        |
| $C_i$      | Closeness coefficient                         |
| $CRF$      | Capital recovery factor                       |
| $C.I.$     | Consistency index                             |
| $C.R.$     | Consistency ratio                             |
| $DNI$      | Direct normal irradiance, W/m <sup>2</sup>    |
| $E$        | Energy rates, kJ/kg                           |
| $ED_{i+}$  | Euclidean distance                            |
| $F$        | Faraday constant, 96,485 C/mol                |
| $F_{mi}$   | Molar flow rate of substance $i$ , mol/s      |
| $FE_i$     | Faraday efficiency of substance $i$           |
| $h$        | Convective heat transfer coefficient          |
| $h_i$      | Enthalpy of stream $i$ , kJ/kg                |
| $I_i$      | Current used for generating substance $i$ , A |
| $i$        | Interest rate                                 |
| $j$        | Current density, A/m <sup>2</sup>             |

|                    |                                                                                                        |
|--------------------|--------------------------------------------------------------------------------------------------------|
| $k_{mn}$           | Data before normalization                                                                              |
| $\dot{m}_i$        | Mass flow rate of stream $i$ , kg/s                                                                    |
| $\max_n(x_n)$      | Maximum values corresponding to the $n$ -th indicator                                                  |
| $\min_n(x_n)$      | Minimum values corresponding to the $n$ -th indicator                                                  |
| $N$                | Number                                                                                                 |
| $n$                | Number of electrons                                                                                    |
| $P$                | Electrolytic cell power, kW                                                                            |
| $\dot{Q}$          | Thermal power, kW                                                                                      |
| $R.I.$             | Random index                                                                                           |
| $S_i$              | Enthalpy of stream $i$ , kJ/(kg·°C)                                                                    |
| $V_a$              | Wind speed, m/s                                                                                        |
| $\dot{W}$          | Electric power, kW                                                                                     |
| $V$                | Applied potential, V                                                                                   |
| $L$                | Project lifetime                                                                                       |
| $X'_{mn}$          | Standardized value of the $m$ -th solution under the $n$ -th indicator                                 |
| $x_{mn}$           | Normalized value of the $m$ -th Pareto solution on the $n$ -th indicator                               |
| $Z_k$              | Cost of the system equipment, USD                                                                      |
| $\alpha_{air}$     | Convective heat transfer coefficient between reflected solar radiation and air, kW/(m <sup>2</sup> ·K) |
| $\varepsilon$      | Emissivity of the receiver                                                                             |
| $\zeta$            | Operation and maintenance coefficient                                                                  |
| $\eta_{EN}$        | Energy efficiency of the system                                                                        |
| $\eta_{EXP}$       | Isentropic efficiency of the expander                                                                  |
| $\eta_{Opt}$       | Optical efficiency of the heliostat                                                                    |
| $\eta_{ORC}$       | Thermal efficiency of the ORC system                                                                   |
| $\eta_{PGE}$       | Power generation efficiency of the system                                                              |
| Abbreviations      |                                                                                                        |
| ACC                | Annual capital cost                                                                                    |
| AHP                | Analytic hierarchy process                                                                             |
| BoP                | Balance of plant                                                                                       |
| CEPCI              | Chemical Engineering Plant Cost Index                                                                  |
| COM                | Component object model                                                                                 |
| CSP                | Concentrated solar power                                                                               |
| CO <sub>2</sub> RR | Carbon dioxide electrochemical reduction reaction                                                      |
| CU                 | Cold utility                                                                                           |
| EXP                | Expander                                                                                               |
| HCT                | Heat collection tower                                                                                  |
| HEX                | Heat exchanger                                                                                         |
| HPT                | High-pressure turbine                                                                                  |
| HU                 | Heat utility                                                                                           |
| LCOM               | Levelized Cost of Methanol                                                                             |
| LCA                | Life cycle assessment                                                                                  |
| LPT                | Low-pressure turbine                                                                                   |
| Net <sub>SCE</sub> | Net specific carbon emission                                                                           |
| NSGA-II            | Non-dominated sorting genetic algorithm-II                                                             |
| OP                 | Output power                                                                                           |
| ORC                | Organic Rankine cycle                                                                                  |
| PSA                | Pressure swing adsorption                                                                              |
| SEP                | Separation                                                                                             |
| SRC                | Steam Rankine cycle                                                                                    |
| TOPSIS             | Technique for Order Preference by Similarity to Ideal Solution                                         |
| TPC                | Total production cost                                                                                  |
| TOC                | Total operating cost                                                                                   |
| TCC                | Total capital cost                                                                                     |

## References

- Adnan, M.A.; Kibria, M.G. Comparative techno-economic and life-cycle assessment of power-to-methanol synthesis pathways. *Appl. Energy* **2020**, *278*, 115614. [\[CrossRef\]](#)
- Lin, D.; Zhang, L.; Pan, C.; Hu, H.; Yang, J.; Tong, B.; Li, Z.; Zhang, X. Techno-economic analysis of offshore green methanol production in South China Sea. *Chem. Eng. J.* **2026**, *527*, 171867. [\[CrossRef\]](#)
- Chen, G.; Cai, J.; Du, W.; Li, J.; Yan, B.; Rajput, M.I.; Tao, J.; Wang, Z.; Gong, S.; Ge, B.; et al. Biomass to green methanol via anaerobic digestion-gasification coupling process: A comprehensive investigation. *Energy* **2026**, *344*, 139830. [\[CrossRef\]](#)
- Li, M.; Yin, S.; Zhou, G.; Li, S.; Peng, B.; Zhang, L.; He, T. Green methanol synthesis from renewable energy integrated with compressed CO<sub>2</sub> energy storage and waste-based systems: Thermodynamic, economic and environmental assessment. *J. Clean. Prod.* **2025**, *526*, 146671. [\[CrossRef\]](#)
- Yoo, Y.; Lee, S.-Y.; Seo, S.-H.; Oh, S.-D.; Kwak, H.-Y. Energy, exergy and thermoeconomic analyses for a power-to-green methanol production plant. *Energy Nexus* **2025**, *19*, 100517. [\[CrossRef\]](#)
- Taslimi, M.S.; Khosravi, A.; Nugroho, Y.K.; Rytter, N.G.M. Optimization and analysis of methanol production from CO<sub>2</sub> and solar-driven hydrogen production: A Danish case study. *Int. J. Hydrogen Energy* **2024**, *69*, 466–476. [\[CrossRef\]](#)
- Lee, B.; Choe, C.; Kim, H.; Kim, A.; Shin, Y.-U.; Haider, J.; Lim, H. Economic Parity Analysis of Green Methanol Synthesis Using Water Electrolysis Based on Renewable Energy. *ACS Sustain. Chem. Eng.* **2021**, *9*, 15807–15818. [\[CrossRef\]](#)
- Li, F.; Chang, F.; Lundgren, J.; Zhang, X.; Liu, Y.; Engvall, K.; Ji, X. Energy, cost, and environmental assessments of methanol production via electrochemical reduction of CO<sub>2</sub> from biosyngas. *ACS Sustain. Chem. Eng.* **2023**, *11*, 2810–2818. [\[CrossRef\]](#)
- Seshadri, G.; Lin, C.; Bocarsly, A.B. A new homogeneous electrocatalyst for the reduction of carbon dioxide to methanol at low overpotential. *J. Electroanal. Chem.* **1994**, *372*, 145–150. [\[CrossRef\]](#)
- Payra, S.; Shenoy, S.; Chakraborty, C.; Tarafder, K.; Roy, S. Structure-sensitive electrocatalytic reduction of CO<sub>2</sub> to methanol over carbon-supported intermetallic PtZn nano-alloys. *ACS Appl. Mater. Interfaces* **2020**, *12*, 19402–19414. [\[CrossRef\]](#)
- Rihm, S.D.; Akroyd, J.; Kraft, M. Modelling a detailed kinetic mechanism for electrocatalytic reduction of CO<sub>2</sub>. *Proc. Combust. Inst.* **2023**, *39*, 5647–5655. [\[CrossRef\]](#)
- Yang, D.; Zhu, Q.; Chen, C.; Liu, H.; Liu, Z.; Zhao, Z.; Zhang, X.; Liu, S.; Han, B. Selective electroreduction of carbon dioxide to methanol on copper selenide nanocatalysts. *Nat. Commun.* **2019**, *10*, 677. [\[CrossRef\]](#) [\[PubMed\]](#)
- Li, F.; Li, Y.; Cao, J.; Carvalho, L.; Lundgren, J.; Engvall, K.; Zhang, X.; Liu, Y.; Ji, X. Combination of CO<sub>2</sub> electrochemical reduction and biomass gasification for producing methanol: A techno-economic assessment. *Energy Convers. Manag.* **2024**, *307*, 118380. [\[CrossRef\]](#)
- Bin, P.; Shuai, L.I.U.; Huixin, L.I.U.; Tianhao, Z. Influence of different working fluids on performance of organic Rankine cycle low temperature waste heat power generation system. *Therm. Power Gener.* **2022**, *51*, 43–48. [\[CrossRef\]](#)
- Khan, M.I.; Asfand, F.; Al-Ghamdi, S.G. Progress in research and technological advancements of thermal energy storage systems for concentrated solar power. *J. Energy Storage* **2022**, *55*, 105860. [\[CrossRef\]](#)
- Zhang, S.; Liu, G. Multi-objective optimization of high-efficiency solar water electrolysis hydrogen production system and its performance. *CIESC J.* **2023**, *74*, 1260–1274.
- Yang, H.; Liu, N.; Li, M.; Gu, M.; Gao, Q. Design and optimization of heat pipe-assisted liquid cooling structure for power battery thermal management based on NSGA-II and entropy Weight-TOPSIS method. *Appl. Therm. Eng.* **2025**, *272*, 126416. [\[CrossRef\]](#)
- Sadeghi, S.; Ghandehariun, S. Thermodynamic analysis and optimization of an integrated solar thermochemical hydrogen production system. *Int. J. Hydrogen Energy* **2020**, *45*, 28426–28436. [\[CrossRef\]](#)
- Sadeghi, S.; Ghandehariun, S.; Naterer, G.F. Exergoeconomic and multi-objective optimization of a solar thermochemical hydrogen production plant with heat recovery. *Energy Convers. Manag.* **2020**, *225*, 113441. [\[CrossRef\]](#)
- Demir, M.E.; Dincer, I. Development of a hybrid solar thermal system with TEG and PEM electrolyzer for hydrogen and power production. *Int. J. Hydrogen Energy* **2017**, *42*, 30044–30056. [\[CrossRef\]](#)
- Abbasi, H.R.; Pourrahmani, H.; Yavarinasab, A.; Emadi, M.A.; Hoorfar, M. Exergoeconomic optimization of a solar driven system with reverse osmosis desalination unit and phase change material thermal energy storages. *Energy Convers. Manag.* **2019**, *199*, 112042. [\[CrossRef\]](#)
- Nabat, M.H.; Soltani, M.; Razmi, A.R.; Nathwani, J.; Dusseault, M.B. Investigation of a green energy storage system based on liquid air energy storage (LAES) and high-temperature concentrated solar power (CSP): Energy, exergy, economic, and environmental (4E) assessments, along with a case study for San Diego, US. *Sustain. Cities Soc.* **2021**, *75*, 103305. [\[CrossRef\]](#)
- Zhang, S.; Li, K.; Zhu, P.; Dai, M.; Liu, G. An efficient hydrogen production process using solar thermo-electrochemical water-splitting cycle and its techno-economic analyses and multi-objective optimization. *Energy Convers. Manag.* **2022**, *266*, 115859. [\[CrossRef\]](#)
- Tera, I.; Zhang, S.; Liu, G. A conceptual hydrogen, heat and power polygeneration system based on biomass gasification, SOFC and waste heat recovery units: Energy, exergy, economic and emergy (4E) assessment. *Energy* **2024**, *295*, 131015. [\[CrossRef\]](#)

25. Bari, S.A.; Fuad, M.; Labib, K.F.; Monjurul Ehsan, M.; Khan, Y.; Hasan, M.M. Enhancement of thermal power plant performance through solar-assisted feed water heaters: An innovative repowering approach. *Energy Convers. Manag. X* **2024**, *22*, 100550. [CrossRef]
26. Manzolini, G.; Lucca, G.; Binotti, M.; Lozza, G. A two-step procedure for the selection of innovative high temperature heat transfer fluids in solar tower power plants. *Renew. Energy* **2021**, *177*, 807–822. [CrossRef]
27. Fan, G.; Ahmadi, A.; Ehyaei, M.A.; Das, B. Energy, exergy, economic and exergoenvironmental analyses of polygeneration system integrated gas cycle, absorption chiller, and Copper-Chlorine thermochemical cycle to produce power, cooling, and hydrogen. *Energy* **2021**, *222*, 120008. [CrossRef]
28. Guo, W.; Liu, S.; Tan, X.; Wu, R.; Yan, X.; Chen, C.; Zhu, Q.; Zheng, L.; Ma, J.; Zhang, J.; et al. Highly Efficient CO<sub>2</sub> Electroreduction to Methanol through Atomically Dispersed Sn Coupled with Defective CuO Catalysts. *Angew. Chem. Int. Ed.* **2021**, *60*, 21979–21987. [CrossRef]
29. Chang, F.; Zhan, G.; Wu, Z.; Duan, Y.; Shi, S.; Zeng, S.; Zhang, X.; Zhang, S. Technoeconomic Analysis and Process Design for CO<sub>2</sub> Electroreduction to CO in Ionic Liquid Electrolyte. *ACS Sustain. Chem. Eng.* **2021**, *9*, 9045–9052. [CrossRef]
30. Jouny, M.; Luc, W.; Jiao, F. General Techno-Economic Analysis of CO<sub>2</sub> Electrolysis Systems. *Ind. Eng. Chem. Res.* **2018**, *57*, 2165–2177. [CrossRef]
31. Plappally, A.K.; Lienhard V, J.H. Energy requirements for water production, treatment, end use, reclamation, and disposal. *Renew. Sustain. Energy Rev.* **2012**, *16*, 4818–4848. [CrossRef]
32. Zhu, X.; Mi, X.; Zhang, H.; Jin, J.; Wang, Y. Research on Carbon Emissions of 135 MWe Tower CSP Plant in the Whole Life Cycle. *Sol. Energy* **2023**, 20–31. [CrossRef]
33. Ministry of Ecology and Environment of the People’s Republic of China; National Bureau of Statistics. Announcement on the Release of 2022 Power Carbon Dioxide Emission Factors. Available online: [https://www.mee.gov.cn/xxgk2018/xxgk/xxgk01/202412/t20241226\\_1099413.html](https://www.mee.gov.cn/xxgk2018/xxgk/xxgk01/202412/t20241226_1099413.html) (accessed on 26 December 2024).
34. Wang, T.; Wang, J.; Lu, C.; Jiang, K.; Yang, S.; Ren, Z.; Zhang, J.; Liu, X.; Chen, L.; Zhuang, X.; et al. Single-Atom Anchored Curved Carbon Surface for Efficient CO<sub>2</sub> Electro-Reduction with Nearly 100% CO Selectivity and Industrially-Relevant Current Density. *Adv. Mater.* **2023**, *35*, 2205553. [CrossRef] [PubMed]
35. Al-Abadi, A.M.; Handhal, A.M.; Abdulhasan, M.A.; Ali, W.L.; Hassan, J.J.; Al Aboodi, A.H. Optimal siting of large photovoltaic solar farms at Basrah governorate, Southern Iraq using hybrid GIS- based Entropy-TOPSIS and AHP-TOPSIS models. *Renew. Energy* **2025**, *241*, 122308. [CrossRef]
36. Saaty, T.L. How to make a decision: The analytic hierarchy process. *Eur. J. Oper. Res.* **1990**, *48*, 9–26. [CrossRef]
37. Saleh, B.; Koglbauer, G.; Wendland, M.; Fischer, J. Working fluids for low-temperature organic rankine cycles. *Energy* **2007**, *32*, 1210–1221. [CrossRef]
38. Qu, Z.; Tian, X. Anti Corrosion System for High Parameter Garbage Power Plant Based on Analytic Hierarchy Process Fuzzy Comprehensive Evaluation. *J. Alloys Metall. Syst.* **2025**, *12*, 100223. [CrossRef]

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