Article

Discussion on the Feasibility of the Integration of Wind Power and Coal Chemical Industries for Hydrogen Production

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Abstract: To improve the utilization rate of the energy industry and reduce high energy consumption and pollution caused by coal chemical industries in northwestern China, a planning scheme of a wind-coal coupling energy system was developed. This scheme involved the analysis method, evaluation criteria, planning method, and optimization operation check for the integration of a comprehensive evaluation framework. A system was established to plan the total cycle revenue to maximize the net present value of the goal programming model and overcome challenges associated with the development of new forms of energy. Subsequently, the proposed scheme is demonstrated using a 500-MW wind farm. The annual capacity of a coal-to-methanol system is 50,000. Results show that the reliability of the wind farm capacity and the investment subject are the main factors affecting the feasibility of the wind-coal coupled system. Wind power hydrogen production generates O_2 and H_2, which are used for methanol preparation and electricity production in coal chemical systems, respectively. Considering electricity price constraints and environmental benefits, a methanol production plant can construct its own wind farm, matching its output to facilitate a more economical wind-coal coupled system. Owing to the high investment cost of wind power plants, an incentive mechanism for saving energy and reducing emissions should be provided for the wind-coal coupled system to ensure economic feasibility and promote clean energy transformation.

Keywords: new energy; wind-coal coupled system; comprehensive evaluation framework; environmental benefits; planning model

1. Introduction

From the development and utilization of coal and oil to the application of new energy sources such as wind and light, low-carbon and clean energy forms are desired. Rapid advancements in the coal chemical industry have promoted economic developments. However, high carbon and low hydrogen contents in coal have inevitably led to the emission of large amounts of carbon dioxide (CO_2). The conversion of coal into natural gas promotes clean coal utilization and considerably reduces pollutant emissions; moreover, it is beneficial for improving the utilization efficiency of coal. However, we must also address high carbon dioxide emissions associated with the conversion of coal to natural gas [1,2]. Intermittent and fluctuating characteristics of new energy power supplies restrict their grid connection [3], severely inhibiting the development of wind power and the photovoltaic industry. Therefore, the use of clean and renewable energy sources solves the problem of significant pollution and energy consumption associated with the coal chemical industry, transforms the high energy consumption of the coal chemical industry into the application scene of new energy, overcomes challenges pertaining to the development of new energy forms, and realizes the mechanism of the common clean, efficient, and sustainable development of regional energy systems.

Considering the integration of the coal chemical industry and new energy sources, the use of wind power and photovoltaic electric energy has been proposed for producing methanol. Such a system comprises a wind power generator, photovoltaic panel, electrolytic cell, methanol production system, rectification device, and other major subsystems. Methanol is produced by the reaction of industrial carbon emissions with hydrogen generated via water electrolysis [4,5]. A photovoltaic–wind power system has been proposed to capture CO_2 and produce electric energy, hydrogen, and methane. Decentralized wind power hydrogen energy storage and coal chemical multienergy coupled systems have also been reported. For the coal-based low-carbon energy strategy in Xinjiang and Shanxi in China, and other new energy sources and coal-rich provinces, a large-scale wind–photohydrogen energy storage/coal multienergy coupled system has been proposed. Wang [6] reported that hydrogen energy coupled with the coal chemical industry boosts the properties of coal raw materials, realizing carbon neutrality [6]. Therefore, an entry point for developing the hydrogen energy–coal-based energy industry has been proposed, including the establishment of the integrated industrial development mode, activation of the properties of coal raw material, and realization of zero CO_2 emissions [7,8].These studies have shown that the coupling of new energy with coal chemical systems (new coal systems) is effective for coordinating the development of new energy and the coal chemical industry and an effective approach for addressing challenges associated with the advancement of coal chemical energy [9,10].

Different from traditional multienergy coupled systems, new coal systems are coupled with the chemical industry and involve more energy forms, energy conversion processes, transmission means, and absorption pathways [11–13]. Therefore, the sustainable development of such energy systems have high requirements in terms of economy, energy saving, environmental protection, and reliability of new coal systems. An integrated wind–photohydrogen system was proposed and evaluated in terms of thermal and energy efficiency [14,15]. Moreover, an economical and environmentally beneficial evaluation framework was proposed for optimizing hydrogen and natural gas supply chains and performing reliability analyses [16,17]. An evaluation standard system was established for the performance evaluation of sustainable development, considering the economic, environmental, and social aspects related to integrated wind–light–hydrogen systems [18]. A new coal system is diverse in terms of the structure and form, and its evaluation indices extend from traditional thermodynamic efficiency indices to environmental and economic indices [19,20]. However, there is a lack of a comprehensive evaluation analysis method and planning model research guided by evaluation criteria for new coal systems. Therefore, a comprehensive, scientific, and rational evaluation system for new coal systems must be developed, its comprehensive performance must be analyzed, and the optimization design of such a system should be guided.

To address the aforementioned problems, we propose a wind-coal coupling energy system (WCCES) and establish a comprehensive evaluation framework for the energy system, which involves the analysis method, evaluation criteria, operation planning, and optimization verification. We also propose a planning model for the proposed WCCES by considering environmental benefits and operation economy. Finally, the effectiveness and feasibility of the proposed system and model are verified by considering a coal–methanol coupling wind farm as an example. Consequently, we provide a theoretical basis for promoting the transformation and upgrading of the energy industry in Xinjiang, Gansu, and other provinces with abundant wind and coal resources in northwestern China to overcome the severe energy shortage and environmental pollution dilemma in China.

2. Wind-Coal Coupling Energy System

2.1. Basic Framework

The basic architecture of the WCCES is shown in Figure 1. It mainly comprises wind power, hydrogen storage, energy distribution, gas distribution, the coal chemical industry, methanol, O_2, and H_2 hybrid power generation systems, and power grid units. The

main process characteristics are described as follows: (1) The wind power system can be a large-scale centralized or decentralized wind farm; (2) The coal chemical system is a coal-to-methanol system, and O_2 can be obtained by wind power hydrogen production to reduce the scale of air separation and save coal fuel; And (3) H_2 is obtained by wind power production, which can eliminate the need for a conversion device, and all the electrical energy required in the production process is clean energy.
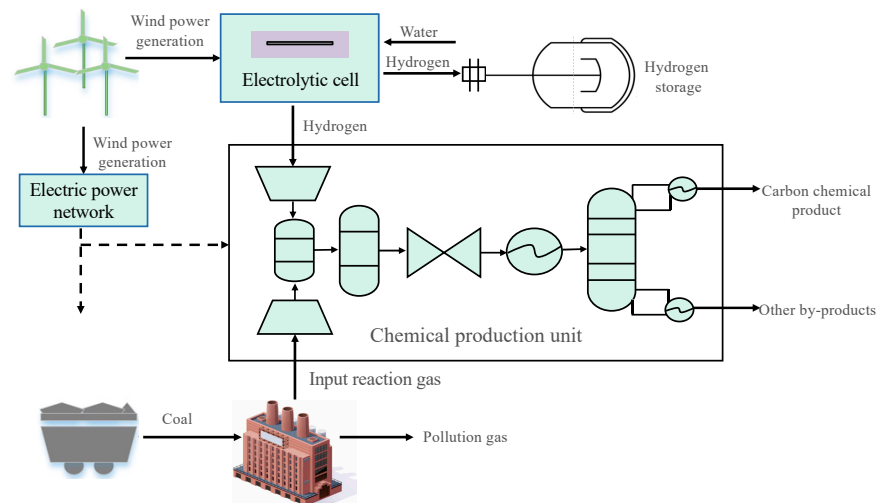
Figure 1. Structural diagram of the WCCES.

2.2. Characterization

Different from traditional coal chemical systems, the WCCES does not directly use fossil energy, such as coal, as the fuel to generate electricity or heat. Instead, it uses new clean electric energy to electrolyze water for hydrogen production, yielding "blue hydrogen." This can increase the storage and utilization of new energy sources during clean coal utilization [21]. Furthermore, with large-scale wind power generation and hydrogen storage as the link, the construction of a new energy-efficient, reliable, and stable "wind-coal energy system" with an independent power supply can realize the integration and complementarity of wind and coal resources in the industrial chain. In this system, electricity is generated using wind energy and coal raw are used. The large-scale hydrogen storage power station for electrolyzing water is a "regulator" for a clean, efficient, reliable, and stable electricity supply. The "cleaners" are raw coal. According to the design of the WCCES, in areas with abundant wind and coal resources, several equivalent capacities several orders larger can be established by relying on large-scale hydrogen storage technology with an energy storage capacity of more than tens of millions of kilowatt-hour. The large-scale WCCES or base at the watt level, which transforms the use of high energy consumption and pollution caused by heavy carbon fossil energy, such as coal, can mitigate the problem of "wind and power curtailment" caused by insufficient demand. This eliminates increasingly severe energy and environmental dilemmas.

As the only power source of the WCCES, the stroke power shows the characteristics of randomness, fluctuation, and intermittently. The power load of the system and the clean use of raw coal require a hydrogen load. Similar to traditional electric power consumption systems and raw materials for coal production, it is relatively stable and continuous, and the contradictions between the stable supply of clean energy, economy, and reliability are more prominent. Therefore, the theory and planning method of "wind-coal energy systems" must be urgently evaluated.

3. Feasibility Analysis

This section provides a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions. A system feasibility analysis

is the basis for evaluating the system performance, characteristics, and main influencing factors. The establishment of a system model based on an analysis method is the first step to improve system performance. Current analysis methods for energy systems mainly include the thermal balance method and exergy analysis based on the first and second laws of thermodynamics. As the processes and forms of the coupled energy system increase, a combination of the thermal balance method and exergy analysis has been proposed to consider the efficiency and accuracy of the system evaluation [22]. Among them, the total energy system organically integrates the energy conversion and utilization processes to meet the multiple objectives with respect to the demand of energy, the chemical industry, and the environment. System analysis methods have been developed based on traditional thermodynamic analysis to combine thermodynamics with economic factors, facilitating "thermodynamic-economic-ecological" analysis [23]. With the rapid development of new energy sources, system reliability will attract considerable attention considering multiple uncertainties.

The system analysis method is closely linked to the evaluation criteria, and the WCCES based on the goal of decarbonization has significant requirements in terms of economy, energy savings, environmental protection and reliability, equipment investment, construction, maintenance and operation, pollution control, other economic indicators, and environmental indicators such as CO_2 and NO [24]. Reliability indicators, including energy and product supply rates, and multiobjective evaluation indicators, including comprehensive performance indicators, have been widely used [25]. Recently, multiple evaluation indices have been combined to form a unified comprehensive evaluation index based on hierarchical analysis, data envelopment analysis, and other methods [26,27].

System analysis methods and evaluation criteria are the benchmarks of system design and planning. Currently, system operation planning methods can be categorized into two types: "system first" and "evaluation first." "System first" grasps the scheduling operation of a system, calculates the specific value of each indicator according to operation data, and conducts comprehensive efficiency evaluations. In "evaluation first," the determined comprehensive evaluation index is considered as the objective function of system planning optimization (or upper and lower limit constraints) to guide system designs. The former can be adjusted based on the requirements of different indicators after the system evaluation, whereas the latter involves the global optimization of comprehensive evaluation indicators.

It is critical to reveal the influence of the relation between system independent variables, parameters, operation scenarios, and evaluation indexes via optimization verification. Moreover, it is important to reflect the integrated correlation between subsystems or functional units and the overall system to study the characteristic law of the WCCES. The comprehensive evaluation framework for the feasibility analysis of the WCCES is shown in Figure 2.
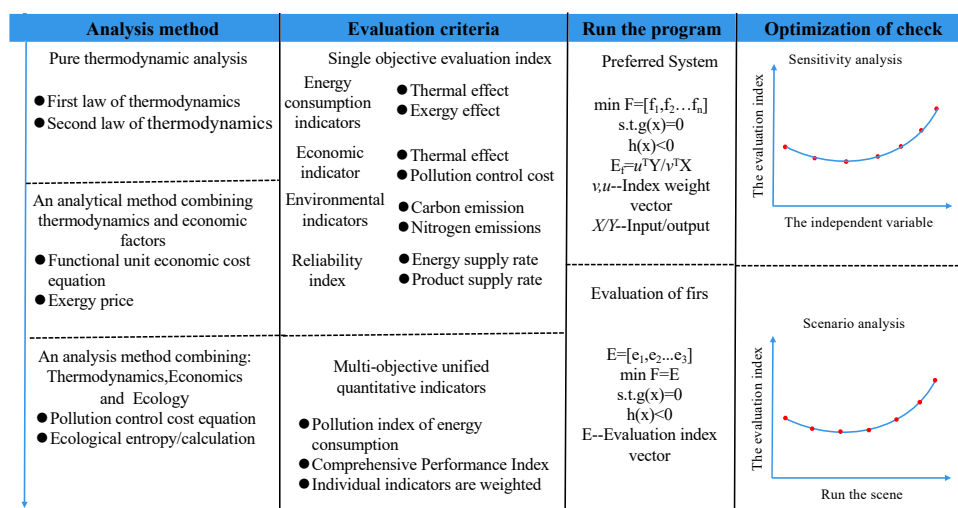

Figure 2. Comprehensive evaluation framework of WCCES.

4. Programming Model

4.1. Objective Function

To meet the planning economic requirements of the WCCES, the maximum net present value F of the total revenue within the planning period is the optimization goal, which is calculated using Equation (1).

$$F = \max(Z_{all} - C_{all}) \tag{1}$$

$$Z_{all} = Z_{sale} + Z_{CO_2} + Z_{end} \tag{2}$$

$$C_{all} = C_{inv} + C_{op} + C_{mc} + C_{ele} \tag{3}$$

where Z_{all}, Z_{sale}, Z_{CO_2}, Z_{end}, C_{all}, C_{inv}, C_{op}, C_{mc}, and C_{ele} represent the net values of the total project output value, system carbon-chemical product sales, carbon dioxide emission reduction benefit, project residual output value, total project input, investment cost, operation cost, maintenance cost, and power purchase cost, respectively.

$$C_{inv} = \sum_{j}^{J} P_j c_j^{inv} \tag{4}$$

$$C_{op} = \sum_{n=1}^{N} \frac{\sum_{j}^{J} P_j c_j^{op}}{(1+r)^{n-1}} \tag{5}$$

$$C_{mc} = \sum_{n=1}^{N} \frac{\sum_{j}^{J} P_j c_j^{mc} + \sum_{j}^{J} P_j^{re} c_j^{re}}{(1+r)^{n-1}} \tag{6}$$

$$C_{ele} = \sum_{n=1}^{N} \frac{\sum_{t=1}^{T} P_t^{ele} c_t^{ele} \Delta t}{(1+r)^{n-1}} \tag{7}$$

$$Z_{sale} = \sum_{n=1}^{N} \frac{\sum_{t=1}^{T} P_t^{load} c_t^{sale} \Delta t}{(1+r)^{n-1}} \tag{8}$$

$$Z_{CO_2} = \sum_{n=1}^{N} \frac{\sum_{t=1}^{T} S_t^{load} c_t^{CO_2}}{(1+r)^{n-1}} \tag{9}$$

$$Z_{end} = \frac{\sum_{j}^{J} P_j^{inv} c_j^{end}}{(1+r)^{N-1}} \tag{10}$$

where P_j represents the initial installed capacity of functional device j; c_j^{inv} is the cost per unit installed capacity; r represents the project discount rate; N represents the project planning period; c_j^{op} denotes the operating cost coefficient of unit capacity; P_j^{re} denotes the replacement capacity of functional equipment; and c_j^{mc} and c_j^{re} represent the maintenance replacement cost coefficients of unit capacity, respectively. The unit price of CO_2 emission reduction and emission reduction are subsidies for the same product.

4.2. Restrictions

4.2.1. System Energy and Material Balance Constraints

The system energy and material balance constraints satisfy the relationship between input and output, which is calculated using Equations (11) and (12).

$$P_t^{wind} + P_t^{grid} = P_t^{load} \tag{11}$$

$$e_{i,t}^{sup} = e_{i,t}^{load} \tag{12}$$

where P_t^{wind}, P_t^{grid}, and P_t^{load} represent the wind farm output, grid input power, and load power demand, respectively, and $e_{i,t}^{sup}$ and $e_{i,t}^{load}$ denote the supply and load demands of element i in time t, respectively.

4.2.2. Constraints on Hydrogen Production Cell of an Electrolyzer

Constraints on hydrogen production unit in electrolytic cell are shown in Equations (13)–(15).

$$H_{PEM}(t) = \delta_{PEM}(t) f(\eta_{PEM}) \omega_{PEM,R} \tag{13}$$

$$\eta_{PEM} = \frac{P_{PEM}(t)}{P_{PEM,R}} \tag{14}$$

$$\delta_{PEM}(t) P_{PEM,\min}(t) \leq P_{PEM}(t) \leq \delta_{PEM}(t) P_{PEM,\max}(t) \tag{15}$$

where $H_{PEM}(t)$ represents the amount of hydrogen produced by the electrolyzer in time t; $f_{(\eta PEM)}$ denotes the efficiency function of the electrolyzer; $P_{PEM}(t)$ represents the input power of the electrolyzer in time t; $P_{PEM,\min}$ and $P_{PEM,\max}$ denotes the electrolysis of the minimum and maximum input powers of the cell, respectively; and $P_{PEM,R}$ represent the rated power of the electrolytic cell. $\delta_{PEM}(t)$ is the variable of the starting state of the electrolytic cell during time t, where 0 indicates the shutdown state and 1 indicates the starting state, i.e., the rated capacity of the ω_{PEM} electrolytic cell.

4.2.3. Hydrogen Storage Unit Constraints

The hydrogen storage capacity changes with injection and output of hydrogen. The mass balance equation and constraint conditions of the storage process are shown in Equations (16)–(18).

$$S_{HS,t+1} = S_{HS,t} + (v_{HS,in}(t) - v_{HS,out}(t)) \Delta t \tag{16}$$

$$0 \leq S_{HS,t+1} \leq S_{HS,\max} \tag{17}$$

$$\begin{aligned} v_{HS,in}^{\min} \leq v_{HS,in}(t) \leq v_{HS,in}^{\max} \\ v_{HS,out}^{\min} \leq v_{HS,out}(t) \leq v_{HS,out}^{\max} \end{aligned} \tag{18}$$

where $S_{HS,t+1}$ and $S_{HS,t}$ represent the total amount of hydrogen stored at times $t + 1$ and t, respectively; $S_{HS,\max}$ represents the maximum capacity of the hydrogen gas storage tank; $v_{HS,in}(t)$ and $v_{HS,out}(t)$ represent the rate of hydrogen injection and output at time t, respectively; Δt represents the interval between times $t + 1$ and t; $v_{HS,in}^{\min}$ and $v_{HS,in}^{\max}$ represent the minimum and maximum values of the rate of hydrogen injection, respectively; and $v_{HS,out}^{\min}$ and $v_{HS,out}^{\max}$ represent the minimum and maximum values of the rate of hydrogen output, respectively.

4.2.4. Other Constraints

Operation constraints of other units are shown in Equations (19)–(22).

$$0 \leq I(t) \leq I^{\max} \tag{19}$$

$$P_\tau^{\min} \leq P_\tau(t) \leq P_\tau^{\max} \tag{20}$$

$$S_{in,\tau}^{\min} \leq S_{\tau}(t) \leq S_{in,\tau}^{\max} \tag{21}$$

$$S_{out,\tau}^{\min} \leq S_{\tau}(t) \leq S_{out,\tau}^{\max} \tag{22}$$

where $I(t)$ represents the number of system operation components at time t; $I^{\max}$ denotes the maximum number of components; $P_{\tau}(t)$ denotes the operating power of component τ; $P_{\tau}^{\min}$ and $P_{\tau}^{\max}$ represent the minimum and maximum operating powers of component τ; respectively; $S_{in,\tau}(t)$ is the input (energy or matter) of component τ at time t; $S_{in,\tau}^{\min}$ and $S_{in,\tau}^{\max}$ denote the minimum and maximum values of the input of element τ; $S_{out,\tau}(t)$ is the output of element τ at time t (energy or substance); and $S_{out,\tau}^{\min}$ and $S_{out,\tau}^{\max}$ are the minimum and maximum values of the output of element τ, respectively.

5. Case Analysis

Because the WCCES is an innovative coupling method between new and traditional energy systems, the aspects of energy consumption, economy, environmental protection, and reliability criteria have yet to be verified. Therefore, this study mainly verifies the economic feasibility of the system based on the economic planning model proposed using a previous comprehensive evaluation framework that considers environmental benefits. In the future, further evaluations on system reliability and environmental protection will be completed using the comprehensive evaluation framework. We built a simulation model of the hydrogen production system in a pluripotent coupling system using MATLAB/Simulink, and the genetic algorithm (GA) was used to solve the model. The theoretical and technical parameters of each component of the wind power hydrogen energy storage and coal chemical multienergy coupled systems are thus obtained.

Considering a wind farm with an installed capacity of 500 MW integrated with a coal-to-methanol system that achieves an annual output of 50,000 tons as an example, the wind-coal coupled methanol-to-methanol system (hereinafter, the coupled system) is shown in Figure 3. The results of the planning scheme are compared with those of the existing coal-to-methanol system in terms of economy, and the economic feasibility of the proposed model and method is verified.
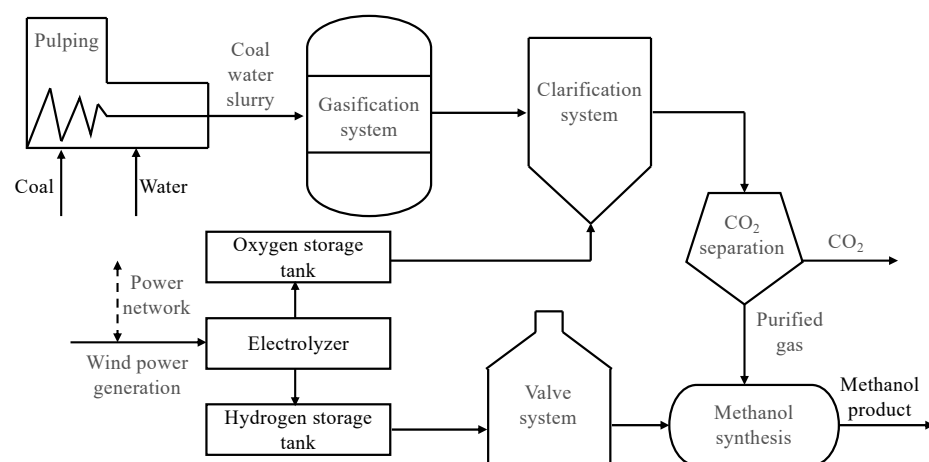
Figure 3. Schematic of wind power coupled methanol production process.

Different from the traditional coal-to-methanol system (Figure 4), the raw materials of hydrogen and oxygen in the coupled system for methanol production were directly obtained from the electrolysis cell and hydrogen storage tank without any air separator separation. Moreover, the electricity consumed for methanol production was obtained from wind farms and power grids. Tables 1–3 present the energy price list, related technical parameters of the traditional coal-to-methanol system and coupled system, and simulation parameters of the coupled system, respectively.
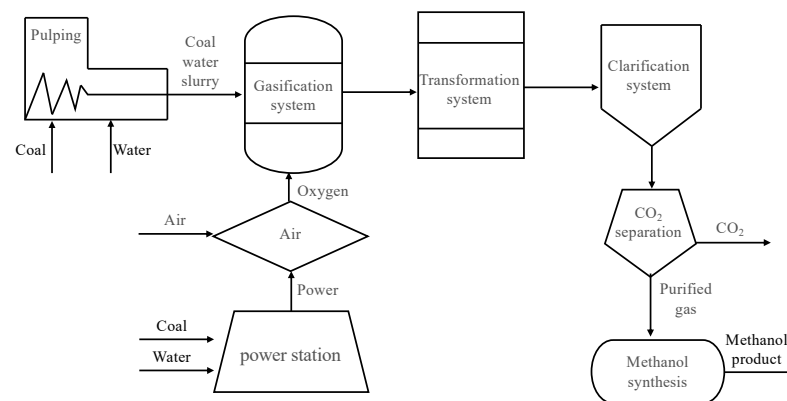
Figure 4. Traditional methanol production system.

Table 1. Energy price.

Title	Unit Price
Industrial water	5 Yuan/t
Coal	300 Yuan/t
Electricity price	0.5 Yuan/kWh
Industrial methanol	2500 Yuan/t
Investment cost	8000 Yuan/kW

Table 2. Technical parameters.

Methanol Energy Consumption and Emissions/t	Legacy System	Wind-Coal Coupled System
Coal consumption in pulping process/t	1.36	1
Water consumption in pulping process/t	4	2
Coal consumption in power generation/t	0.24	-
Water consumption in power generation/t	6	-
Electrolytic water consumption/t	-	1
Water electrolysis consumes electricity/MWh	-	6.25
CO_2 emission from power generation/t	0.56	-
CO_2 separation emission/t	2.08	0.4
System energy consumption	46,892.8	22,500

Table 3. Simulation parameters.

Title	Simulation Parameters
Electrolytic cell investment cost	10,000 Yuan/kW
Hydrogen storage tank investment cost	1200 Yuan/Nm^3
Electrolytic cell operating costs	1.6 Yuan/kWh
CO_2 emission subsidy	0.04 Yuan/kg

Tables 2 and 3 show that, compared with the traditional coal-to-methanol system, for every ton of methanol produced, the WCCES reduces water consumption and CO_2 emissions by 2 and 2.24 tons, respectively, and consumes 0.6 tons of coal and the electricity of 6.25 MWh. If energy consumption is expressed in terms of the calorific value, the energy consumption of the traditional system and WCCES is 46,892.8 and 22,500 kJ, respectively. Furthermore, investment costs related to the electrolysis cell and hydrogen storage tank and the operation cost of the electrolysis cell increase.

A GA was used to solve the proposed programming model. The number of individuals in each generation was 120, the variation rate was 0.8, the crossover rate was 0.2, the calculation accuracy was 10^{-6}, and the number of iterations was 1000. Typical daily curves of the wind farm output and methanol output are shown in Figure 5. These curves can be

used to analyze the economic distribution of the coupled system under different capacity reliabilities of wind farms (Figure 5). Among them, the capacity credit of wind power is defined as the ratio of capacity, which is equivalent to the conventional generation to serve the load at the same reliability level. It is an important indicator for measuring its contribution to the adequacy of the power system. Scheme 1 represents the self-built wind farm of the coupled system, and the capacity reliability proportionally increases with the typical daily wind power and methanol production (Figure 5) (0.2). Scheme 2 shows that the coupled system does not build its wind farm, and the electricity required is purchased at the price shown in Table 1.
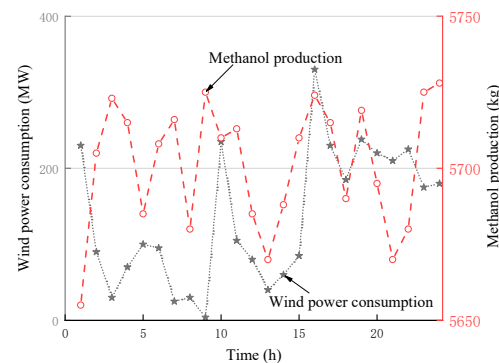

Figure 5. Daily active power delivered to the grid and methanol production distribution curve.

The operation mode of the coupled system in scenario 1 is described as follows. The wind farm generates electricity to produce hydrogen. When the power supply of the wind farm is insufficient, the hydrogen storage tank is introduced. When the hydrogen storage quantity is insufficient, electricity is purchased from a large power grid to produce hydrogen to ensure reliable hydrogen supply. Figure 6 shows optimization results for different trusted capacities of wind farms in the coupled system (interval [0.2, 0.36]) under scenario 1. Table 4 shows the specific costs and benefits of the coupled system when the trusted capacities of the wind farm are 0.2 and 0.36. With an increase in the number of the trusted capacities of the wind farm, the rated power of the planned electrolytic cell and the capacity of the hydrogen storage tank decrease and the system income increases. When the trusted capacity of wind farms increases from 0.2 to 0.36, the typical daily total power generation of wind farms with the coupled system increases from 2400 to 4317 MWh and the cost of purchasing power and producing hydrogen is saved by 309 million yuan in the planning period. Furthermore, there is no need to increase the rated operating power of the electrolytic cell and the capacity of the hydrogen storage tank to reduce the cost of electricity purchase and the investment cost of the system.
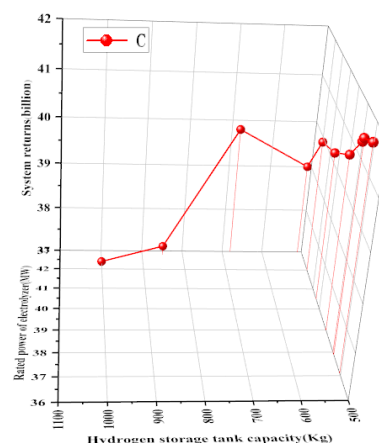

Figure 6. Optimization result of case 1.

Table 4. Comparison of optimization results.

Planning Indicators	Trusted Capacity (0.2)	Trusted Capacity (0.36)
Rated power of electrolyzer/MW	1.36	1
Hydrogen storage tank capacity/L	4	2
Hydrogen production storage investment cost/100 million yuan	0.24	-
Power purchase cost/100 million yuan	6	-
Wind power consumption/100 million KWH	-	1

Figures 7 and 8 show the detailed operation of the coupled system on a typical day when the trusted capacities of the wind farm are 0.2 and 0.36, respectively. Studies have shown that as the capacity of wind farms increases, the hydrogen production process of the electrolytic cell becomes more stable. When the trusted capacity increases to 0.26, the coupled system does not need to purchase electricity from a large power grid and a stable hydrogen supply can be maintained by coordinating the charging and discharging processes of the hydrogen storage tank.
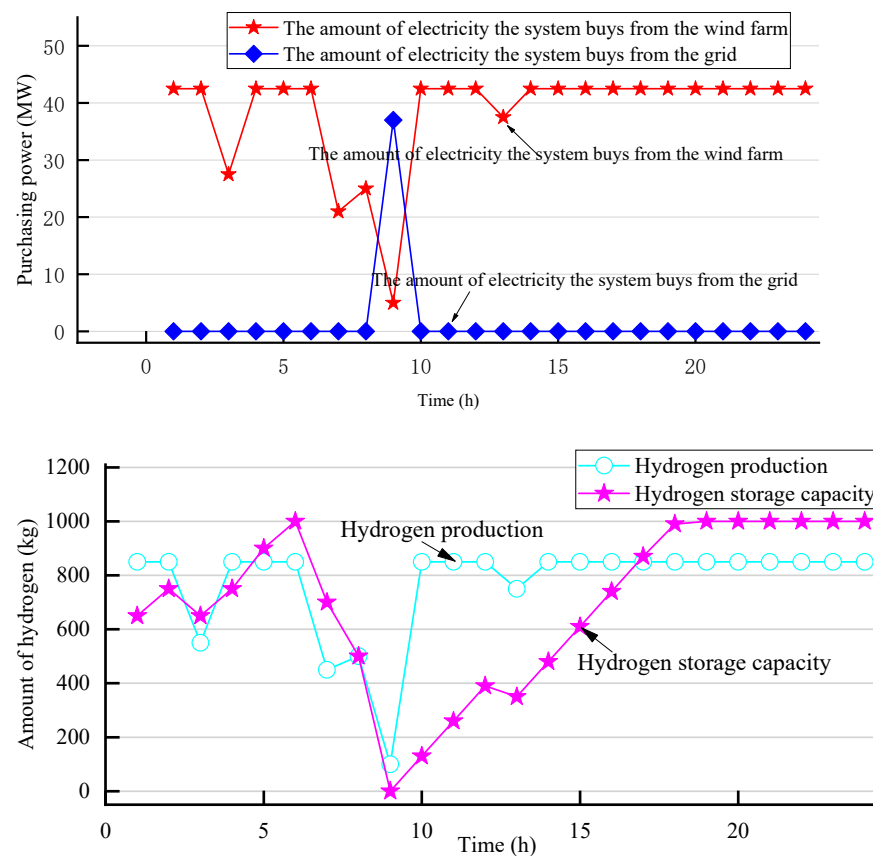

Figure 7. Operation results when trusted capacity is 0.20.

Table 5 shows the credibility of wind farms under different coal-to-methanol schemes at 0.3; the price of methanol is 2500 yuan per ton, and the coal-to-methanol system is 20 years old. Comparing the operating benefits of coupled schemes 1 and 2, the results show that scheme 1 is more economical. Although the investment, operation, and maintenance costs for the entire life cycle of the wind farm are higher, the wind farm is built with a trusted capacity of 0.3. The coal system does not need to purchase electricity from the grid to produce hydrogen. Table 5 shows that compared with scheme 2, scheme 1 will reduce emissions by 22.4 million tons during the planning period and the emission reduction benefit will be 2.048 billion yuan. If the emission reduction benefit of wind power generation is not considered, the total benefit of coupled scheme 1 is far less than that of

scheme 2. Therefore, to promote the clean transformation of the energy system, the WCCES should be provided with an energy saving and emission reduction incentive mechanism at some stage, as the investment cost of wind farm construction is relatively high.
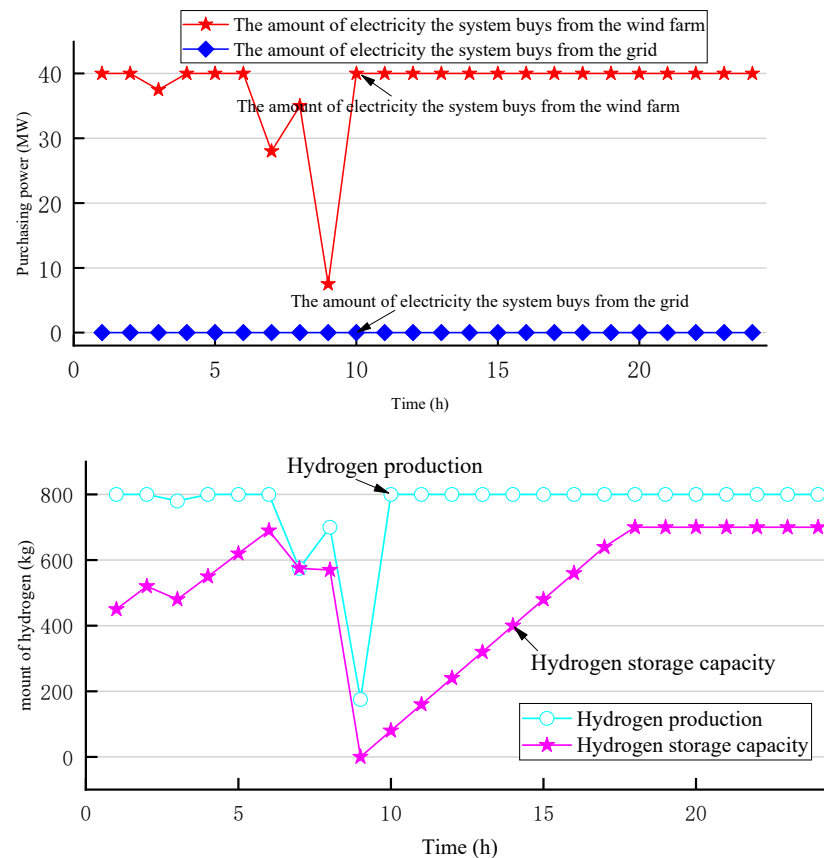

Figure 8. Operation results when trusted capacity is 0.36.

Table 5. Comparison between schemes in terms of economy.

Planning Indicators	Scheme 1	Scheme 2
Comprehensive investment cost of wind farm/100 million Yuan	40	-
Wind farm operation and maintenance costs/100 million Yuan	1.2	-
Hydrogen production storage investment costs/100 million Yuan	4.01	4.03
Investment cost of methanol from coal/100 million yuan	1.0	1.0
Coal consumption cost/100 million Yuan	6.86	6.86
Water consumption cost/100 million Yuan	0.45	0.45
Power purchase cost/100 million Yuan	0	32.41
Methanol yield/100 million Yuan	57.2	57.2
CO_2 emission reduction/ten thousand tons	2240	-
Emission reduction benefits/100 million Yuan	20.48	-
Wind power consumption/100 million KWH	64.82	-
Total revenue/100 million yuan	24.16	12.45

6. Challenges

The operating efficiency of the WCCES is an issue to be considered, including the efficiency of water electrolysis, efficiency of hydrogen storage and release, and efficiency of hydrogen transportation and utilization [28]. Moreover, all or most of the electrical energy required by the WCCES is provided by intermittent new energy sources. Coupled with the fluctuation of electrical and hydrogen loads, the system supply and demand balance problem is highlighted under the uncertainty of multitime and multiple space coupling [29].

As an emerging green energy-saving industry, hydrogen production using the WCCES has not reached a fixed form. The operation management of the WCCES includes safety services for hydrogen production, transmission, storage and application links to ensure hydrogen quality standards, reduce various losses, and improve economic benefits for promoting operational and personal safety. The innovation and development of wind turbines are critical for wind power hydrogen production technology. Currently, doubly fed and permanent-magnet direct-drive wind turbines are the most widely used. In-depth research on the structure and working characteristics of permanent-magnet direct-drive synchronous generators and doubly fed asynchronous generators and their adaptability to hydrogen production using wind power has yet to be performed.

7. Conclusions

To solve the problem of joint clean, efficient, and sustainable development of coal and new energy, the WCCES was proposed. The feasibility of the WCCES, including analysis methods, evaluation criteria, operation planning methods, and optimization verification, was established by constructing a comprehensive evaluation framework. Based on this, a WCCES planning model considering environmental benefits and operating economics was established. Finally, the economic feasibility of the WCCES was analyzed by considering a coal-to-methanol coupling wind farm as an example. The findings of this research are presented below.

1. The credibility of the wind farm capacity and its investment subject are the main factors affecting the feasibility of the WCCES. The higher the credibility of the wind farm, the lower the proportion of electricity price costs.
2. Constrained by electricity prices and incentives for environmental benefits, the self-built wind farm can make the WCCES more economical while achieving an output similar to that obtained using the methanol production plants.
3. As the trusted capacity of the wind farm increases, the planned rated power of the electrolytic cell and the capacity of the hydrogen storage tank decrease and the WCCES revenue increases. When the trusted capacity of the wind farm increases to 0.26, the coupled system does not need to purchase electricity from a large power grid and a stable hydrogen supply can be maintained by coordinating the charging and discharging processes of the hydrogen storage tank.
4. Coupled scheme 1 is more economical than coupled scheme 2. Scheme 1 will reduce emissions by 22.4 million tons during the planning period, and the emission reduction benefit will be 2.048 billion yuan if the emission reduction benefits of hydrogen production using wind power are not considered.

Therefore, to promote the clean transformation of the traditional energy system and considering the case when the investment cost of wind farm construction is high, the WCCES should be provided with an energy saving and emission reduction incentive mechanism. The reliability of the WCCES can be further evaluated with further research, guided by a comprehensive evaluation framework.

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