

Article

How Would Structural Change in Electricity and Hydrogen End Use Impact Low-Carbon Transition of an Energy System? A Case Study of China

Nuobei Zhang, Zheng Li, Xiaoying Zheng * and Pei Liu * 

State Key Lab of Power Systems, Tsinghua-BP Clean Energy Center, Department of Energy and Power Engineering, Tsinghua University, Beijing 100084, China; znb22@mails.tsinghua.edu.cn (N.Z.); lz-dte@tsinghua.edu.cn (Z.L.)

* Correspondence: zhengxiaoying617@hotmail.com (X.Z.); liu_pei@tsinghua.edu.cn (P.L.)

Abstract: Driven by global targets to reduce greenhouse gas emissions, energy systems are expected to undergo fundamental changes. In light of carbon neutrality policies, China is expected to significantly increase the proportion of hydrogen and electricity in its energy system in the future. Nevertheless, the future trajectory remains shrouded in uncertainty. To explore the potential ramifications of varying growth scenarios pertaining to hydrogen and electricity on the energy landscape, this study employs a meticulously designed bottom-up model. Through comprehensive scenario calculations, the research aims to unravel the implications of such expansions and provide a nuanced analysis of their effects on the energy system. Results show that with an increase in electrification rates, cumulative carbon dioxide emissions over a certain planning horizon could be reduced, at the price of increased unit reduction costs. By increasing the share of end-use electricity and hydrogen from 71% to 80% in 2060, the unit carbon reduction cost will rise by 17%. Increasing shares of hydrogen could shorten the carbon emission peak time by approximately five years, but it also brings an increase in peak shaving demand.



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Keywords: scenarios; bottom-up model; China; electricity; hydrogen

1. Introduction

The issue of climate change caused by human activities has become increasingly severe [1], resulting in significant impacts on human production and life [2]. Therefore, it is necessary to take measures to address this issue [3]. One of the important factors is carbon emissions resulting from the use of energy. Fossil energy still accounts for the majority of global energy consumption. According to BP's scenario forecast [4], the proportion of fossil energy will drop from 84% (2018) to 21.7% (2050) to achieve near-zero emissions. The global energy system is expected to undergo an inevitably profound low-carbon transition, both on the supply side and on the terminal demand side. Achieving low-carbonization of the energy system requires efforts on both ends. At one end, it is necessary to reduce the dependence on fossil fuels on the supply side and expand the scale of renewable energy. At the other end, it is essential to increase the demand for end-use electricity and hydrogen. Many studies have highlighted the potential for significant growth in hydrogen and electricity in the future [4–6]. Compared with electricity, hydrogen started its development later, but it is easier to store than electricity, so it can be used to compensate for some of the shortcomings of electricity in industrial and transportation activities [4]. In addition, hydrogen and electricity compete in some industries, such as the transportation industry, where hydrogen fuel cell vehicles may replace electric vehicles. The failure to anticipate the future development of electricity and hydrogen and their relationship may result in unclear goals in energy system planning and unnecessary planning costs. To clarify how the growth of these two forms of energy affects the energy system and the

difference between their impacts, it is necessary to conduct research to provide guidance, such as determining the transition objectives and reducing the overall costs.

The current research mainly focuses on scenario analysis of different policies that may occur, and the scenarios are mainly set through macroeconomic parameters or energy technology parameters. Zhou et al. [7] used the bottom-up LBNL model to evaluate the role of China's energy efficiency policy in the process of low-carbon transformation of the energy structure under the scenarios of continuous improvement and accelerated improvement. The study showed that the growth of China's carbon emissions is unlikely to continue in this century. Liu et al. [8] selected the China TIMES model and predicted China's energy demand from 2050 under reasonable assumptions about the future economy. Dai et al. [9] built two scenarios from the perspective of renewable development and assessed the impact of large-scale renewable development on the economy and environment by 2050. Mi et al. [10] proposed the input–output optimization model IMEC, set two scenarios according to the different years of the peak, and pointed out the impact of the earlier peak on China's economic growth. Matthias et al. [11] proposed a qualitative and quantitative method for scenario setting through the calculation of multiple models and analyzed two scenarios focused on different technologies. Franziska et al. [12] set six socio-economic qualitative scenarios, qualitatively analyzed Germany's natural gas investment, pointed out the limitations of traditional methods, and pointed out that developing economic scenarios would help improve economic policy assessment. Guo et al. [13] conducted a scenario analysis on building energy consumption, taking China as a case, and pointed out that the carbon peak time is expected to be 2020–2035. Duan et al. [14] compared the results of various models, pointed out that China would reduce its carbon emissions by 90% with the goal of 1.5 °C under the policy scenario, explained the importance of negative emission technology in the future, and pointed out that the power industry needs to complete decarbonization before 2050. Alex et al. [15] studied the changes in energy demand, price, and emissions in Kenya by setting coal, nuclear energy, and renewable scenarios based on the LEAP model. Zhang et al. [16] set different scenarios, analyzed the contribution of emission reduction measures in different periods, and analyzed the uncertainty of key parameters. Zheng et al. [17] set three different scenarios through Bayesian hierarchical models and analyzed the changes in carbon emissions in different departments and provinces.

Previous studies focused on the impact of different policies on the carbon emission trajectory. However, little attention has been paid to the impact of the increase in end-use electricity and hydrogen proportions in the energy system, which is more intrinsic. Ignoring these two factors may well lead to an unclear description of the energy substitution process and, furthermore, increase the uncertainty in technical planning. Moreover, most studies set scenarios based on policy changes, among which the settings between different scenarios are very different and often do not reflect the change process between scenarios, which will lead to overlooking important trends. Furthermore, most modeling tools are commonly developed by institutions in developed countries, which may encounter challenges when applied to developing countries, such as data scarcity, inadequate infrastructure, a low level of marketization in the economy, and dynamic changes in political stability and economic growth [18]. Consequently, when existing modeling tools are applied to developing countries like China, there will be insufficient spatiotemporal differentiation and inadequate characterization of infrastructure, making it difficult to address the challenges faced.

Therefore, based on the existing multi-regional and multi-period system optimization model, this study analyzes the impact of the increase in the end use of electricity and hydrogen in the transition of energy structure through the following three steps: (a) Assume different proportions of end-use electricity and hydrogen to set two groups of different scenarios. (b) Calculate the energy supply system planning scheme under the corresponding scenario through the optimization model. (c) Compare the schemes under different scenarios to determine the impact of hydrogen upgrading and electrification deepening on energy supply system planning.

The China Regional Energy Supply System Optimization Model (CRESOM) used in this study is mainly applied to realize energy supply system planning with minimum cost under the established policy conditions through six multi-regional and multi-period sub-models, including coal, oil, natural gas, power, and hydrogen. Previously, CRESOM was used for research. CRESOM was applied to the study of the transition path of the energy supply system to the 50% non-fossil energy target in 2050 [19] and developed a blueprint for carbon-neutral transition [20], but it was not used to study the impact of the penetration growth of fossil energy alternatives (electricity, hydrogen). CRESOM can describe the substitution intensity of electricity and hydrogen in different degrees and can also reflect the relationship between different types of energy. For example, the increase in demand for renewable power has led to an increase in natural gas power, which has affected the supply of natural gas.

The selection of China as a suitable case study is primarily based on the following considerations: (a) The energy system is large in scale and complex in structure, and the calculation of the model can provide a feasible transition program. (b) The proportion of fossil energy is high. In 2021, China's fossil energy consumption accounted for 82.5% of total energy consumption and 446 billion tons of standard coal [21], and the range of change in the process of transition is large. Providing guidance through quantitative calculation is conducive to the steady decline of fossil energy. (c) China has put forward its own carbon emission reduction target, and the demand for hydrogen and electricity at the national level is clearly positioned, so the growth of electricity and hydrogen in the foreseeable future will be large. Currently, China's electricity production has continued to increase, rising from 10.4% in 2010 to 20.4% in 2022 [21]. The electrification rate at the end-use level has also steadily risen, with electricity accounting for approximately 26.9% of national final energy consumption in 2021 [22]. Additionally, China is the world's largest producer of hydrogen, with an annual production of approximately 33 million tons [23]. China has also set specific short-term targets for its own electrification and hydrogen development, aiming for electricity to account for around 30% of final energy consumption by 2025 [24] and to establish a hydrogen industry system by 2035 [23]. However, long-term development plans remain unclear. Thus, this study takes China as a case to study the impact of the increase in end-use electricity and hydrogen proportions in the energy system through multi-scenario calculations, aiming to provide guidance for its transition and provide experience for other countries that take fossil energy as the main energy and have high emission reduction ambitions.

The contributions of this work compared to existing studies are mainly reflected in the following three points. Firstly, a novel idea of scenario setting is put forward. The scenario setting is based on the penetration strength of alternative energy sources (electricity and hydrogen) for fossil energy, and the end-use proportion of electricity and hydrogen is set. Secondly, the progressive scenario setting method makes up for the problem that there are great differences in different scenarios in previous studies. Through this method, we can derive some qualitative conclusions from the progressive changes between scenarios. Thirdly, we imagine the massive growth of hydrogen demand and explore its impact on the energy system, which is not considered in other studies.

The structure of this paper is as follows. In Section 2, the methodology is introduced, including the model structure and scenario design. The case study and the results under various scenarios will be introduced in Section 3. In Section 4, the conclusions are summarized.

2. Materials and Methods

The scenario analysis based on the optimization model is chosen as the method. We can seek the optimal solution under different hypothetical scenarios for the future and obtain valuable guidance for transition by computing the optimal model.

2.1. The Structure of CRESOM

CRESOM is mainly used for the optimal planning of energy supply systems under the given low-carbon transition strategy. The basic parameters of CRESOM are set as follows: In terms of time, CRESOM is calculated with the month as the time step, and the optimized time period is 2016–2060. Geographically, due to the difficulty of data acquisition, CRESOM only includes 30 provinces, cities, and autonomous regions in China, excluding Hong Kong, Macao, Taiwan, and Tibet. From the perspective of terminal energy varieties, CRESOM includes coal, refined oil, natural gas, heat, electricity, and hydrogen. For primary energy varieties, CRESOM includes coal, crude oil, natural gas, onshore wind power, offshore wind power, solar power, hydropower, and nuclear power. In terms of the end-use energy sector, CRESOM includes eight different energy consumption sectors: agriculture, construction, industry, retail, transportation, urban residents, rural residents, and others. The total cost of CRESOM is the cost of different links in the energy supply chain, including the costs required for production, processing, import, storage, transportation, infrastructure construction, operation, and maintenance. Since CRESOM's spatial resolution only covers provinces, only trans-provincial transportation is considered in terms of transportation costs, not intra-provincial transportation.

The main inputs of the model include historical data used to describe the current energy supply and demand and infrastructure construction, prospective data used to describe future economic growth, energy intensity and energy technology cost, and scenario data used to describe emission reduction policies and carbon policies. The GDP, energy intensity, historical input data, and costs are consistent across all scenarios, with the GDP growth rate and energy intensity sourced from BP Outlook [25]. The sources for costs and historical data are as follows: taking the example of the electricity model, future cost data are derived from previously published research by others [26], while historical monthly electricity generation data are obtained from the National Bureau of Statistics [27]. The data on electricity generation, grid connection, and energy storage facilities, as well as efficiency, are sourced from the annual development report of the Chinese power industry [28].

The model first calculates the energy demand by the categories of each terminal energy department in each region from 2016 to 2060 through the terminal energy demand forecasting model; then, the final planning scheme is obtained by minimizing the total cost through the thermal power system optimization model.

The output data include the forecast of the future and the planning scheme at different stages. The structure of the model is shown in Figure 1.

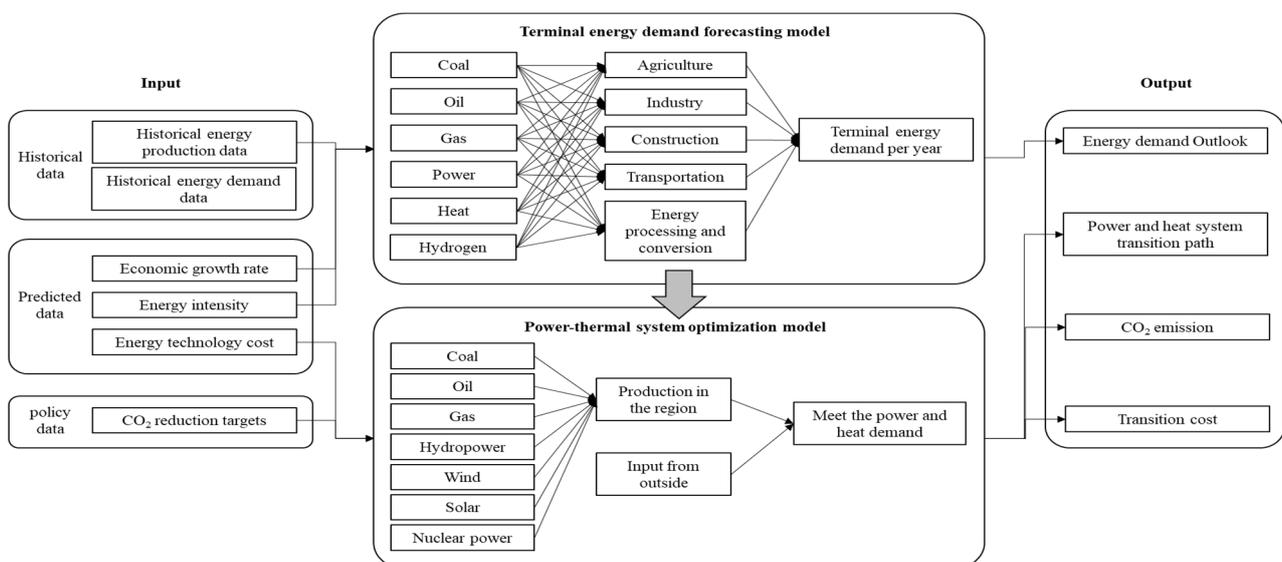


Figure 1. The structure of CRESOM.

2.2. The Operation Logic of CRESOM

The operation logic of the CRESOM sub-module is shown in Figure 2. It first splits the prediction results of energy demand according to different energy types and then inputs them into different sub-models for optimal planning. The power sub-model mainly inputs the power demand from terminals and the power demand for hydrogen production from the hydrogen sub-model, and then completes the planning of primary energy demand. There are four main sources of coal in the coal model: one part is from the terminal coal demand, one part is from the coal needed for heating demand, one part is from the coal needed for hydrogen production, and one part is from the coal needed for power generation. The demand of the natural gas model is similar. The hydrogen sub-model mainly meets the demand for hydrogen energy at the terminal and the demand for hydrogen energy for heating, and the main ways to supply hydrogen energy include electricity to produce hydrogen, coal to produce hydrogen, and natural gas to produce hydrogen. The input of the oil sub-model is the simplest, that is, the terminal oil demand.

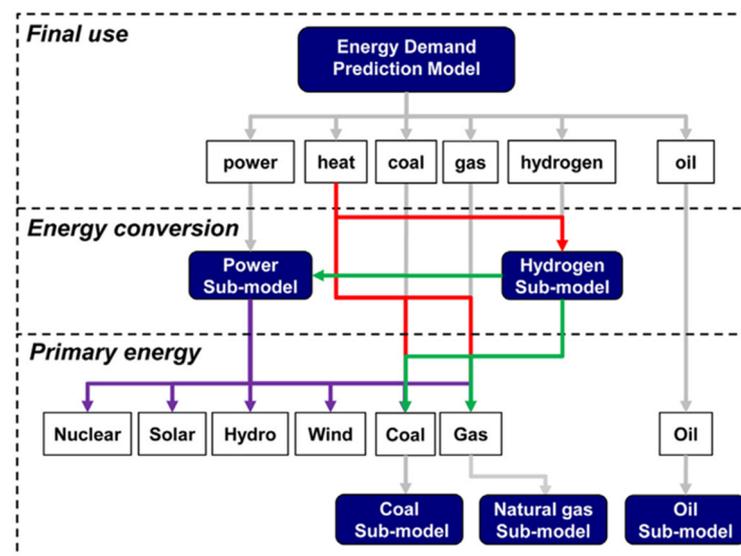


Figure 2. The operation logic of CRESOM.

In different energy system planning sub-models, the bottom-up modeling method is adopted, and the idea of superstructure modeling [29] is applied to optimize the planning by minimizing the cost function. The total cost mainly includes the following five costs: 1. Infrastructure construction costs. The infrastructure in an energy system refers to the equipment necessary for energy production, import, transportation, storage, processing, and other links, such as power stations, transmission and distribution networks, natural gas networks, coal mines, oil refineries, etc. 2. Operation and maintenance costs. This refers to the costs required for the operation of infrastructure. 3. Transportation costs, such as the costs incurred in the transportation of imported oil and natural gas, the transportation costs of natural gas pipelines, and the costs of transporting coal by rail or road. 4. Import costs. This is the cost obtained by multiplying the price of imported goods by the import volume. 5. Fuel cost, such as the cost of fuel consumption in the hydrogen production process.

2.3. The Implementation of Energy Substitution Process in the Model

In the prediction sub-model, the parameters we input mainly include the GDP growth rate, energy intensity reduction rates, and transition policy assumptions. Then, based on the data of the benchmark year, the model calculates the energy demand for different regions and varieties of future economic growth results. The scenario assumptions are mainly realized by setting the alternative factor ES in the prediction sub-model [30]. The formula for predicting energy demand in the model is shown in Equation (1), where ED is

the energy demand for different regions and different production departments of different varieties at time t , $GDPR$ is the GDP growth rate for different regions and departments at time t , $EIRR$ is the energy intensity reduction rate for different regions and departments at time t , and ES is the amount of energy substitution for different varieties of energy in department d relative to energy variety e . In the scenario parameter setting, different energy substitution intensities are mainly assumed.

$$ED_{r,d,e,t} = ED_{r,d,e,t-1} \times (1 + GDPR_{r,d,t}) \times (1 - EIRR_{r,d,t}) + \sum_{ee} (ES_{d,ee,e,t} - ES_{d,e,ee,t}) \quad (1)$$

Due to the different efficiencies of different substitution methods, the impact on energy demand is different. In order to balance the impact caused by efficiency, a substitution coefficient is introduced. For example, in some areas of industry, hydrogen can be used as a substitute for coal as a raw material, but the efficiency of the two process flows is different, and the energy demand after substitution is different. Therefore, the substitution coefficient $SC_{In,CO,HY}$ is introduced. Relevant coefficients are introduced in other different industries' substitution processes, such as the substitution coefficient $SC_{Tr,OI,ELE}$ introduced for electric vehicles in the transportation industry replacing fuel vehicles [30], the substitution of natural gas for coal in the power industry introduce $SC_{Po,CO,NG}$, and so on.

$$ES_{In,CO,HY,t} = ES_{In,HY,CO,t} \times SC_{In,CO,HY} \quad (2)$$

$$ES_{Tr,OI,ELE,t} = ES_{Tr,ELE,OI,t} \times SC_{Tr,OI,ELE} \quad (3)$$

$$ES_{Po,CO,NG,t} = ES_{Po,NG,CO,t} \times SC_{Po,CO,NG} \quad (4)$$

3. Results

3.1. Scenario Setting

Scenario analysis helps reduce the uncertainty in formulating low-carbon policies to achieve the goal of transitioning to a low-carbon economy. China has set the goal of having a carbon peak in 2030 and being carbon neutral in 2060. To approach this goal, the permeability of electricity and hydrogen is the core influencing factor. However, these two forms of energy have similar effects on carbon emission reduction. Thus, this study focuses on the impact of electricity and hydrogen in the process of the energy transition and shows their different impacts on the energy system through different scenarios. Therefore, two groups of scenarios are established. One scenario focuses on a high proportion of electricity, while the other emphasizes a high proportion of hydrogen. The relevant settings for the scenarios are shown in the tables below. Various studies have differing expectations of end-use electricity proportion, such as 45% (rapid), 50% (net zero), and 34% (BAU) for BP's three scenarios in 2050 [4], 50% (NEZ) for IEA's scenario in 2050 [5], and 19%, 27%, and 31% for WEC's three scenarios in 2040 [6]. This article estimates the range of China's end-use electricity proportion in 2060 based on previous studies, which is one of the key scenario parameters regulated by the intensity of energy substitution. The other one is the end-use hydrogen proportion; however, due to the lack of research, the estimation of end-use hydrogen proportion mainly refers to the domestic reports of China [31] and has been set within a reasonable range.

In high-proportion electricity scenarios, we mainly address the following question: how will using electricity as the main alternative energy source to fossil fuels affect the energy supply system? Therefore, in the scenario settings, as shown in Table 1, end-use electricity demand will be the main driver of growth, and hydrogen will have a slight increase as a regulating energy source for electricity growth in this scenario. In high-proportion hydrogen scenarios, we do not consider the joint growth of hydrogen and electricity due to practical considerations, as this may lead to a too-high sum of their proportions. Instead, we consider the substitution effect of hydrogen on electricity and thus set it under a high joint total proportion, as shown in Table 2. In this case, we envision a

future scenario: after a breakthrough in hydrogen technology in the future, a large increase in hydrogen and its substitution of electricity and fossil fuels are very likely. Therefore, how this process will affect the energy supply system is a question worth studying.

Table 1. The setting of the high-proportion electricity scenario.

Scenario	EH65	EH68	EH71	EH74	EH77	EH80
End-use electricity proportion in 2060 (%)	55	57.5	60.1	62.6	65.2	67.7
End-use hydrogen proportion in 2060 (%)	10	10.5	10.9	11.4	11.8	12.3
Total proportion (%)	65	68	71	74	77	80

Table 2. The setting of the high-proportion hydrogen scenario.

Scenario	H12	H15	H18	H21	H24	H27	H30
End-use electricity proportion in 2060 (%)	65	62	59	56	53	50	47
End-use hydrogen proportion in 2060 (%)	12	15	18	21	24	27	30
Total proportion (%)				77			

3.2. High-Proportion Electricity Scenario Results

3.2.1. Overall and Sub-Sectors of Carbon Emissions

China is the largest carbon emitter in the world. According to the statistical data from BP [32], China's carbon emissions reached 10.5 Gt in 2021, accounting for 31% of the world's total emissions. There is still a long way to go to achieve its proposed target. Under the high-proportion electricity scenario, carbon emissions have a similar trend in general, but there are certain differences in emissions near 2060 and between different sectors. As depicted in Figure 3a, carbon emissions exhibit a decline after peaking in 2025, with the promotion of electrification accelerating the reduction in carbon emissions. In Figure 3b, carbon emissions exceeded 10 billion tons in 2020, primarily concentrated in the industrial and power generation sectors. With the advancement of electrification, overall carbon emissions across various scenarios are projected to drop below 2 billion tons by 2060. The most significant changes occur in the power generation, heating, and industry sectors. By 2060, the primary carbon emissions will be predominantly concentrated in the industrial sector, gradually decreasing with the varying rates of electrification across scenarios.

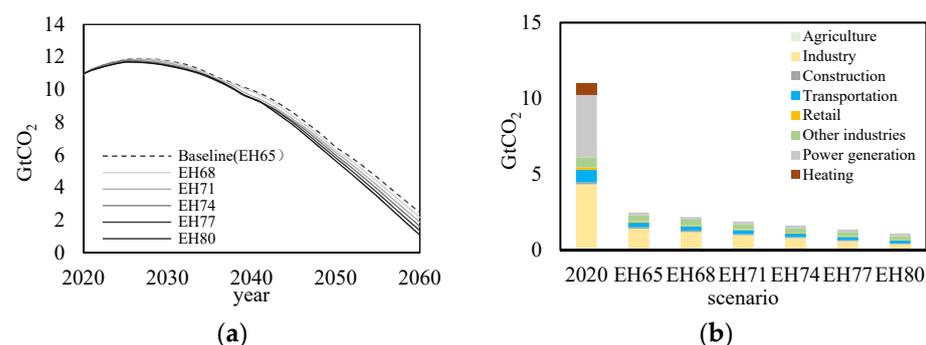


Figure 3. Changes in carbon emissions under the high-proportion electricity scenario. (a) Total carbon emissions. The darker the color, the higher the end-use electricity proportion. The following figures are the same; (b) carbon emissions from different industries. The data for 2020 are on the far left, the other data represent 2060 emissions under different scenarios.

3.2.2. Fossil Energy Supply Structure

The supply structure of fossil energy will undergo significant changes with the substitution of electricity and hydrogen in the future. The changes in the supply structure are shown in Figure 4. The main characteristics are as follows: 1. In the context of China's

carbon neutrality goals, the supply of fossil energy is exhibiting a trend of reaching a peak and then declining. Both coal and oil are expected to peak in 2025, while natural gas is projected to peak in 2035. 2. The change in natural gas supply rises first and then falls, then slowly rises and fluctuates to a certain extent. At the same time, the higher the terminal electricity ratio, the higher the natural gas demand in 2060, which is mainly affected by natural gas power generation. 3. The impact on the fossil fuel supply structure tends to affect import and export volumes first and ensure its own production volume trend, which is consistent with China's domestic policy trend. For example, both oil and natural gas supplies are increased or reduced by import volume, while production volume changes little (Figure 4c–f). Regarding coal, with its limited import volume, production volume can only be reduced (Figure 4a,b).

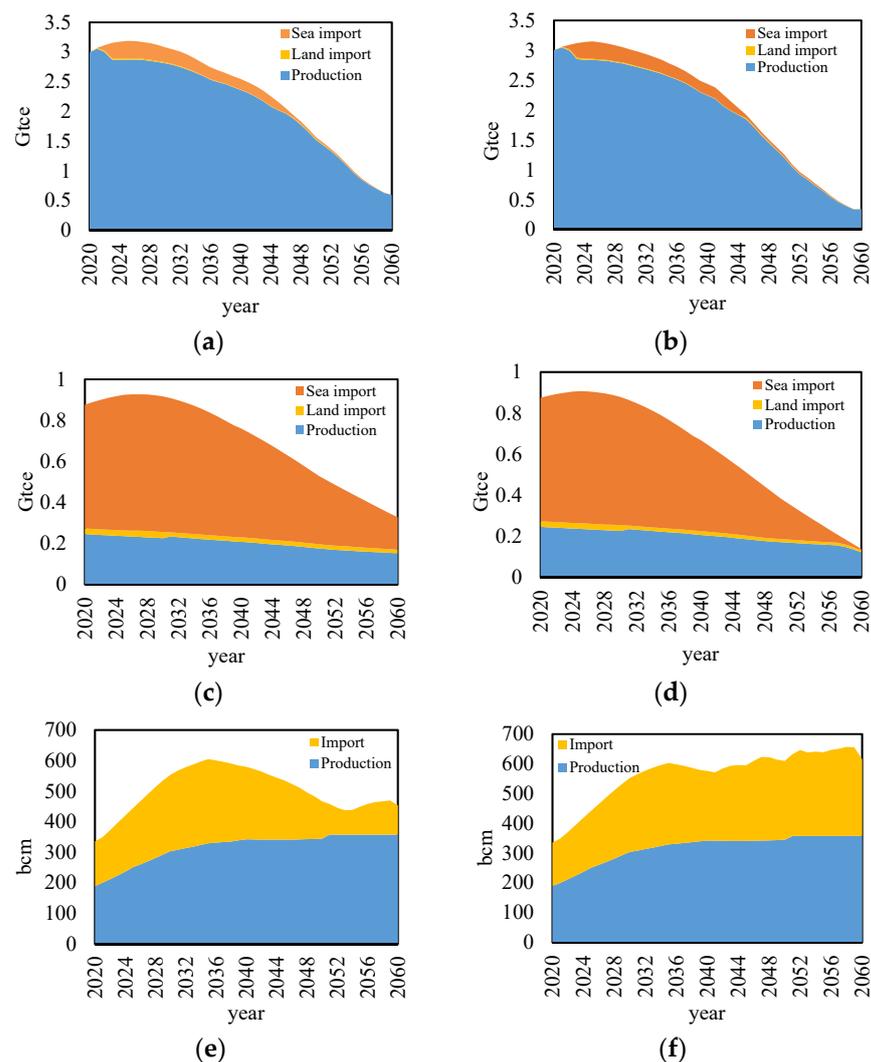


Figure 4. Changes in fossil energy supply structure under the high-proportion hydrogen scenario. (a) Coal supply structure in EH65; (b) coal supply structure in EH80; (c) oil supply structure in EH65; (d) oil supply structure in EH80; (e) natural gas supply structure in EH65; (f) natural gas supply structure in EH80.

Compared to other research, this study is more aggressive in its findings due to the higher proportion of electricity to hydrogen in the end-use. For example, while BP predicts that fossil fuels will account for approximately 67.1% of China's primary energy consumption in 2040 [28], in this study, under the EH65 scenario, the proportion of fossil fuels in primary energy consumption is 60%, and 55.4% under the EH80 scenario. Correspondingly, the supply of fossil fuels is also lower, but the overall trend is similar. For instance,

BP predicts that in 2040, China's domestic natural gas production will be 365 bcm, with 273 bcm imported. According to the results of this study, under the EH65 scenario, domestic natural gas production is 342 bcm, with imports at 237 bcm (Figure 4e).

3.2.3. Power Supply Structure

The power system is undoubtedly the most affected sector in the high-proportion scenario. In the results, we mainly divide the power sources into non-fossil electricity and fossil electricity for presentation. The model also considers energy storage and CCS technology.

Non-fossil power is the main alternative energy in the high-proportion electricity scenario, and it shows a significant increase, as shown in Figure 5a. EH80 (2060) and EH65 (2060) increase by 9.3 and 8.5 times, respectively, compared to the year 2020, reaching 9.94 TW and 9.18 TW accordingly. For fossil power, the capacity of fossil power remains stable from 2020 to 2040 and declines after 2040 (Figure 5b). However, with the increase in the end-use electricity proportion, the installed capacity of thermal power declines slowly and even has a slight growth near 2060. In 2060, fossil power installations will be dominated by coal power with CCS and gas power with CCS, which mainly play a peak-shaving role. This phenomenon indicates that rising non-fossil power installations lead to the growth of power fluctuations. Although non-fossil power has increased significantly and fossil power has declined to varying degrees, the higher the electrification rate, the higher the proportion of fossil energy (Figure 5c). In the EH80 scenario, fossil power accounts for 15%. This shows that with the increase in electrification rates, fossil energy will not disappear but play a more important role.

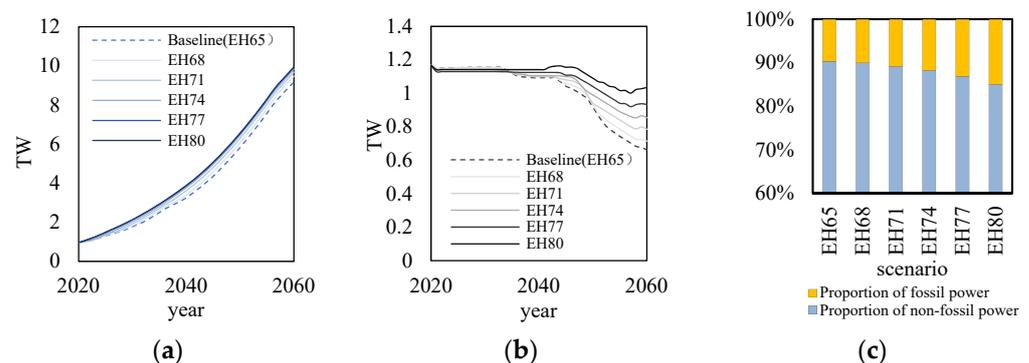


Figure 5. Changes in power supply structure under the high-proportion electricity scenario. (a) Non-fossil power installation capacity; (b) fossil power installation capacity; (c) proportion of fossil power and non-fossil power in 2060.

With the increasing penetration of non-fossil energy sources, especially renewable energy sources, seasonal fluctuations in power generation systems are inevitable. Therefore, regulating peak loads in power systems under a high-proportion electricity scenario is an important issue. In the model, there are mainly two types of regulation methods: one is energy storage, mainly in the form of electrical energy storage; the other is coal power and natural gas power, which serve as peak-load regulators. According to the optimization model results, as the renewable installed capacity increases, electrical energy storage first increases until around 2055 and then decreases (Figure 6a). An interesting phenomenon is that with the increase in the end-use electricity proportion, the scale of electrical energy storage gradually decreases near 2060, while according to the model output results, coal power and natural gas power operating hours decrease, and installed capacity share increases continuously, especially that of natural gas power. Additionally, we find that, in 2060, wind power will be fully developed in most regions, while photovoltaic will still have some development potential. Under the EH80 scenario, the installed capacity of wind power and PV in coastal provinces with large energy consumption and northwestern

provinces accounts for more than 90% (Figure 6b). With the continuous increase in end-use electricity demand, the system does not choose to develop the remaining wind and solar resources but instead chooses to increase the installed capacity of natural gas power generation and natural gas power generation with CCS (Figure 6c). This indicates the importance of natural gas power generation with CCS under a high proportion of end-use electrification. On the one hand, compared with electric energy storage, it is not only a kind of power generation energy source that can meet the electricity demand but also can play a peak shaving role. Compared with wind and solar power generation, it is a more stable zero-carbon power generation energy source. Therefore, as natural gas power generation with CCS increases, the use of electric energy storage decreases, and the installation speed of wind and solar power slows down.

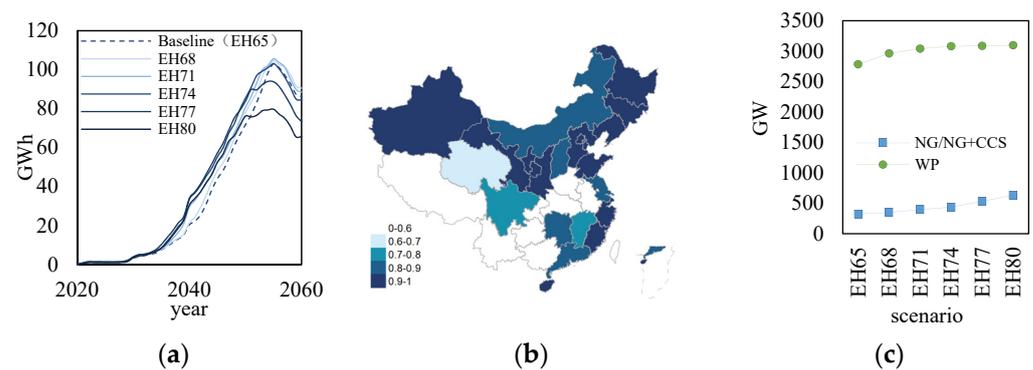


Figure 6. Changes in power storage and fossil power in 2060 under the high-proportion electricity scenario. (a) Power storage; (b) distribution of wind and photovoltaic installed capacity proportion under the EH80 scenario; (c) gas power and wind power capacity in 2060.

3.2.4. Different System Costs

The costs of the system reflect the state of the economy during the transition process. This paper defines and analyzes different costs from different perspectives to study the relationship between the economy and other important physical quantities, such as carbon emissions, electricity generation, etc., under different transition scenarios.

To analyze the impact of different intensities of substitution of electricity and hydrogen on the cost of the entire energy system, this study firstly defines the total cost of the entire energy system from a macro perspective. The total accumulated cost is calculated as the sum of the total accumulated costs of various subsystems (coal, oil, natural gas, electricity, hydrogen). Then, we focus on the power system and use the system cost of unit power generation to reflect the impact of increasing the electricity share at the end-use on the economic performance of the power system. This is calculated by dividing the cumulative cost of the power system from 2020 to 2060 by the cumulative electricity generation. Lastly, we use $cost_{CUTCRC}$ (cumulative unit transition carbon reduction cost) to analyze the cost-effectiveness of carbon reduction during the transition process. This indicates how effective the carbon reduction effect is for the cost paid by the energy system, as shown in Equation (5). The molecular part is the total cost of all scenarios compared with the scenario without an energy substitution policy. The denominator part is the carbon dioxide reduction in all scenarios compared to the scenario without an energy substitution policy. This reflects the cost performance of the system's carbon reduction.

$$cost_{CUTCRC} = \frac{\sum_{2020}^{2060} cost_{year_{EH}} - \sum_{2020}^{2060} cost_{year_{BAU}}}{\sum_{2020}^{2060} CO_{2_{BAU}} - \sum_{2020}^{2060} CO_{2_{EH}}} \quad (5)$$

The calculation results of the model can be summarized in the following points: 1. The increase in electricity's share leads to a rise in the total accumulated cost. The total accumulated cost increases by 26.4% in 2060 (EH65 to EH80), the main reason for this is the increase in electricity and natural gas costs. Additionally, we find a significant rise in

the cost of the natural gas supply system between scenarios EH74 and EH80, primarily attributed to the aforementioned increase in the installed capacity of natural gas (Figure 7a). 2. The system cost of unit power generation increases with the increasing electricity share in the end-use, and this cost of EH80 is 20.3% higher than that of EH65, indicating that excessive electrification reduces the cost-effectiveness of power system construction and operation. The decrease in cost-effectiveness is mainly due to the high installation costs associated with the addition of CCS. 3. Excessive promotion of electrification will cause a decline in carbon reduction cost-effectiveness. As the end-use electricity proportion increases, the $cost_{CUTCRC}$ continues to rise, especially when the total proportion is greater than 74%, where the proportion of end-use electricity in EH80 is 6% higher than that in EH74, but the $cost_{CUTCRC}$ is 17% higher. The main reasons for this can be attributed to several factors. Firstly, as mentioned earlier, the increase in the installed capacity of natural gas and natural gas CCS has resulted in a decrease in the cost-effectiveness of the power system. Additionally, in terms of natural gas supply, the main increase has been in the relatively expensive imported natural gas, leading to a rise in costs for the natural gas supply system. Simultaneously, the increased demand for electricity at a higher proportion of end-use has necessitated the addition of more fossil fuel-based power generation, thereby adding an additional burden for emission reduction.

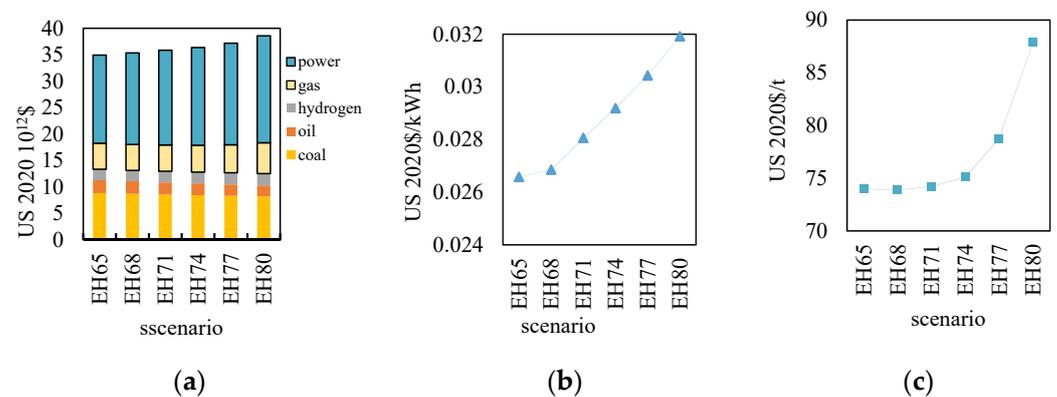


Figure 7. Changes in system costs under the high-proportion electricity scenario. (a) Total accumulated cost; (b) system cost of unit power generation; (c) $cost_{CUTCRC}$.

3.3. High-Proportion Hydrogen Scenario Results

3.3.1. Total Emissions and System Costs

In terms of overall emission reduction capacity, hydrogen and electricity did not show significant differences. In the high-proportion hydrogen scenario, the sum of the end-use electricity and hydrogen proportions among different scenarios is the same, resulting in little difference in carbon emission trajectories and annual system costs close to 2060. The main difference in results is reflected in the accelerated peak year due to the increase in hydrogen (Figure 8a). From an economic standpoint, since the differences in annual costs are not significant in the high-proportion hydrogen scenario, the analysis is based on the accumulated total cost of annual costs between 2020 and 2060. A high demand for hydrogen leads to a higher cumulative total cost. The total accumulated cost of H15 decreased by 0.5% compared with H12, while the total accumulated cost of H30 increased by 2.7% compared to H12 (Figure 8b). From the perspective of the cost performance of emission reduction. The $cost_{CUTCRC}$ increases and then decreases with the increase in hydrogen, which shows that both lower and higher end-use hydrogen proportions have good emission reduction cost performance (Figure 8c).

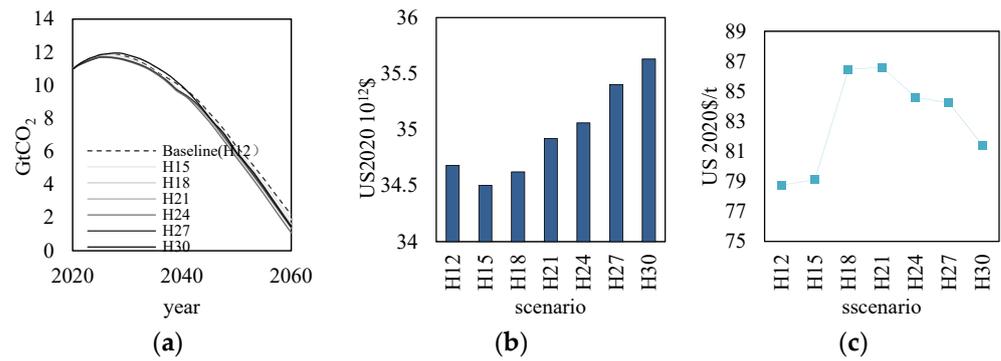


Figure 8. Changes in carbon emissions and system costs under the high-proportion hydrogen scenario. (a) Carbon emissions; (b) total accumulated cost; (c) $cost_{CUTCRC}$.

3.3.2. Power Supply Structure

In the high-proportion hydrogen scenario, the substitution effect of hydrogen at the end-use level causes a significant change in the power supply structure. This is mainly reflected in two aspects.

Firstly, the substitution effect of hydrogen at the terminal promotes a reduction in end-use electricity demand. However, in the model, hydrogen mainly relies on a green electricity supply, which in turn creates a certain demand for electricity. Therefore, the overall electricity demand decreases only slightly. The cumulative electricity generation in the scenario H30 decreased by 1.2% compared to the scenario H12. The installed fossil capacity shows a decline after a steady change over time (Figure 9a). As hydrogen increases, the decline time of fossil capacity advances. The decline time of H12 is 2046, while the decline time of H30 is 2025. At the same time, the decline speed of the scenario with a higher hydrogen proportion is relatively slow. On the other hand, the reliance of hydrogen on green electricity promotes an increase in the proportion of renewable electricity and a decrease in fossil fuel-based electricity. In the H30 scenario, the proportion of non-fossil fuel electricity reaches 33% in 2020 and 81% in 2060. At the same time, as the proportion of hydrogen energy increases, the proportion of non-fossil fuel power generation continues to increase.

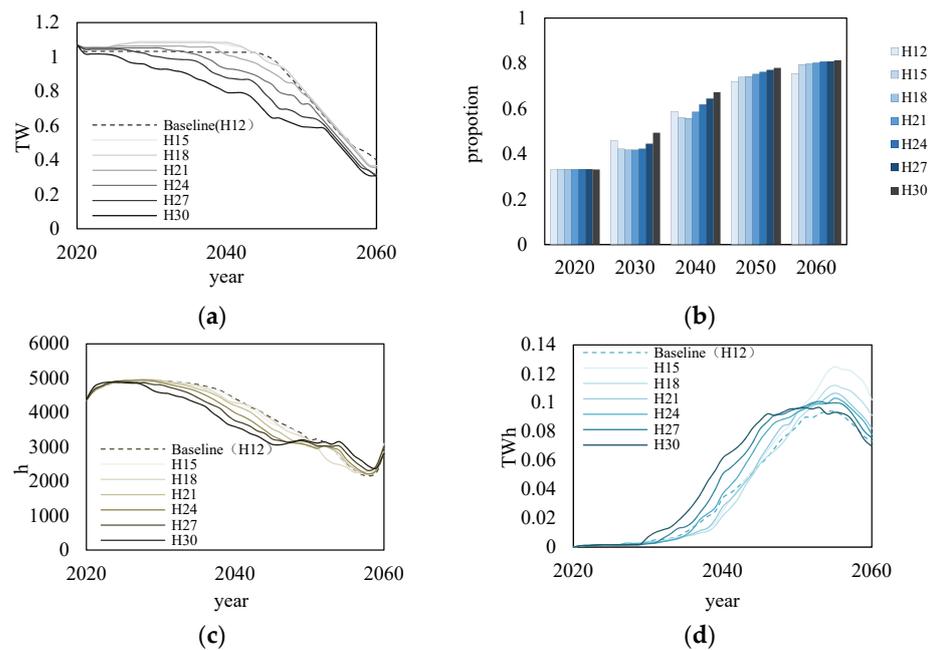


Figure 9. Changes in power supply structure under the high-proportion hydrogen scenario. (a) Fossil capacity; (b) proportion of non-fossil power generation; (c) operating hours of coal power; (d) energy storage capacity.

Secondly, the significant increase in the proportion of renewable energy generation resulting from the rise in hydrogen shares leads to an increase in peak shaving demand, which is manifested in the early decline of coal power generation hours and the change in energy storage pressure. The operating hours of coal power decrease in advance with the increase in hydrogen (Figure 9c), which means that hydrogen promotes the transition of coal power from the main power generation energy to energy with a peak-shaving function. This advance also shows that the development of hydrogen in 2030–2050 brings a large number of wind power and photovoltaic installations that need a large amount of energy storage for peak shaving (Figure 9d). From 2050 to 2060, it can be seen that electric energy storage decreases with the increase in hydrogen in the last ten years. Therefore, the increase in hydrogen causes an increase in energy storage pressure from 2030 to 2050, but the decrease in electricity reduces the energy storage pressure from 2050 to 2060.

3.3.3. Hydrogen Supply Structure

In the model, it is mainly assumed that hydrogen is produced through renewable power generation. The production capacity of hydrogen increases with an increase in the proportion of hydrogen. When the hydrogen proportion reaches 30%, the hydrogen production capacity will exceed 3000 bcm (Figure 10a). In the background of high-proportion hydrogen, the production of hydrogen consumes a considerable amount of electricity. According to the calculation results (Figure 10b), more than 20% of renewable electricity is used for hydrogen production in all scenarios. In 2060, the proportion reaches more than 50% in H30. Even the scenario with the lowest proportion of hydrogen energy needs to use 30% of electricity for hydrogen production. From the overall trend, the proportion of hydrogen production electricity consumption in renewable power generation grows fast during 2030–2060.

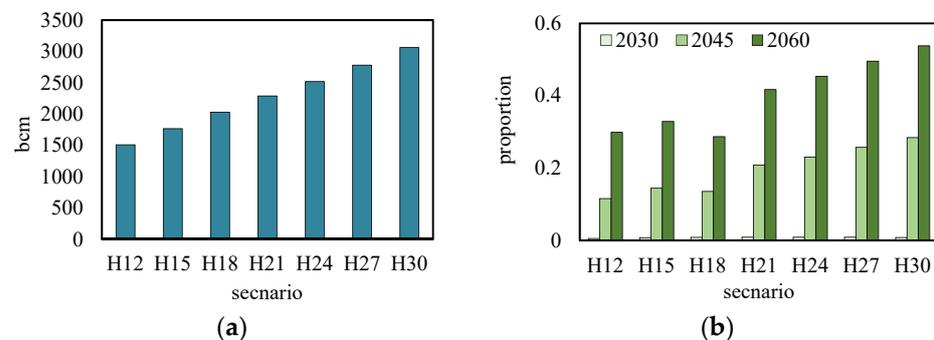


Figure 10. Changes in hydrogen supply structure under the high-proportion electricity scenario. (a) Hydrogen production capacity in 2060; (b) proportion of hydrogen production electricity consumption in renewable power generation.

3.3.4. Regional Supply Structure of Power and Hydrogen

The regional variation in hydrogen substitution for electricity is worth studying. This study explores it from the perspective of the geographical distribution of energy production and storage. The increase in hydrogen affects the regional distribution of electricity and hydrogen production, which is mainly reflected in the following points. Firstly, with the growth of demand for hydrogen, the distribution of power capacity shows a decrease in some western provinces and an increase in coastal eastern provinces (Figure 11a,b). The geographical distribution of hydrogen production capacity varies mainly in the increase in hydrogen production capacity in the provinces of southwest, northwest, and southeast coastal regions (Figure 11c,d). Secondly, power capacity and hydrogen production capacity show a certain degree of geographical dependence. With the increasing demand for hydrogen, the northwest region and southeast coastal provinces may become important provinces for electricity generation and hydrogen production in the future.

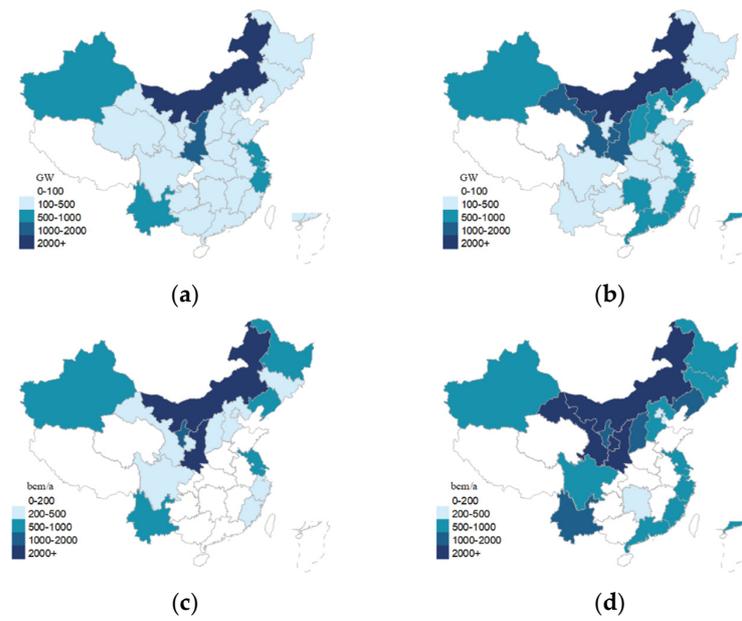


Figure 11. Regional changes in hydrogen production capacity and power capacity under the high-proportion hydrogen scenario in 2060. (a) Distribution of power installation in H12; (b) distribution of power installation in H30; (c) distribution of hydrogen production in H12; (d) distribution of hydrogen production in H30.

In terms of electricity storage, the increase in demand for hydrogen reduces the overall demand for electricity storage. At the same time, from the perspective of regional distribution, the storage of electricity becomes more uniform. The power storage in the eastern coastal provinces increases, while the power storage in the northwest, southwest, and northern provinces decreases (Figure 12a,b). The distribution of hydrogen storage is mainly concentrated in the eastern coastal provinces, which have a large energy consumption. As the proportion of hydrogen increases, its distribution gradually moves to the north (Figure 12c,d).

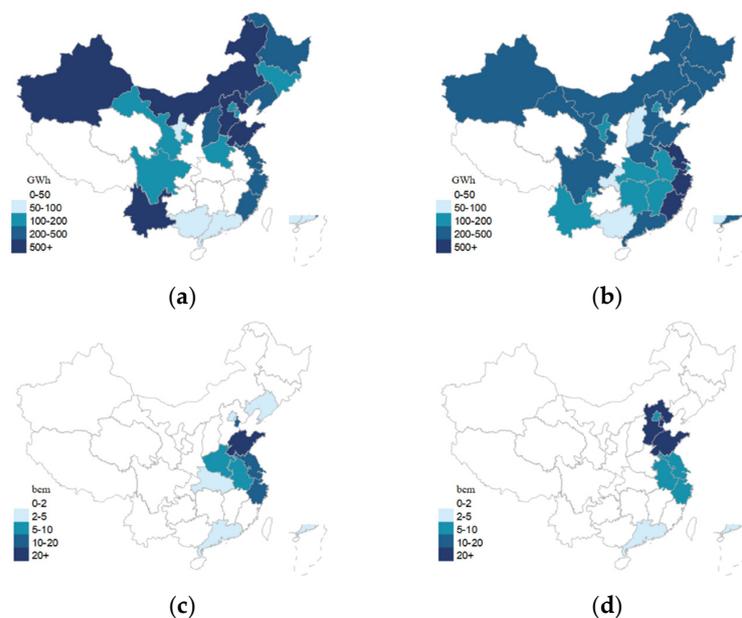


Figure 12. Regional changes in power storage and hydrogen storage under the high-proportion hydrogen scenario in 2060. (a) Distribution of power storage in H12; (b) distribution of power storage in H30; (c) distribution of hydrogen storage in H12; (d) distribution of hydrogen storage in H30.

4. Conclusions

Based on the optimization model CRESOM, this study reveals the impact of the growth of electricity and hydrogen on the low-carbon transition of the energy supply system through two groups of scenario calculations. Through scenario calculations, calculations have been conducted for potentially extreme scenarios in the future, such as EH80 and H30, demonstrating the impact of the excessive increase in the share of electricity and hydrogen at the end-use stage. Additionally, some patterns have been identified through the gradual changes between scenarios, such as variations in electricity storage. The implications can be summarized as follows.

In high-proportion electricity scenarios, the impact of increased electrification in the end-use on the entire energy system can be summarized as follows: firstly, the substitution of electricity promotes emission reductions at the end-use and leads to a decrease in overall carbon emissions, and secondly, the increase in electrification rate promotes the development of more renewable energy. In addition, natural gas power generation and natural gas combined with CCS play an important role, not only in providing peak-shaving capabilities but also in meeting the growing demand for electricity. These options have advantages over the development of electric energy storage and wind and solar energy, but they come with higher costs and some carbon emissions. Therefore, the overall cost-effectiveness of carbon reduction decreases as the electrification rate increases.

In high-proportion hydrogen scenarios, the impact of hydrogen on the entire energy system can be summarized as follows: Firstly, according to the model settings, hydrogen primarily substitutes electricity at the end-use, with a focus on green hydrogen production methods. Consequently, there will be a certain demand for electricity, which offsets the overall electricity generation, resulting in a slight decrease as the proportion of hydrogen energy increases. Secondly, hydrogen primarily stimulates an increase in renewable power generation within the energy system, leading to a greater need for peak-shaving capabilities. As a result, the operating hours of fossil fuel power plants decline earlier, and the deployment of energy storage technologies advances. For geographical distribution, the generation of electricity and hydrogen show a certain degree of overlap, while energy storage mainly depends on electricity generation, and the storage of hydrogen is mainly distributed in coastal provinces with high energy demand.

The practical implications brought about by the scenario analysis of the model can be summarized as follows: 1. The proportion of electricity and hydrogen at the end-use should not be excessively high, as excessively high electrification and hydrogen proportions increase total costs. Future policies should prioritize the promotion of electrification and support the development of hydrogen energy as secondary. The model's computational results suggest that, by 2060, the combined proportion of electricity and hydrogen should not exceed 74%, with the proportion of hydrogen energy at the end-use stage not exceeding 15%. 2. The development of gas power combined with CCS technology plays an important role in achieving carbon neutrality goals. It provides peak-shaving capabilities and alleviates pressure on energy storage, and it replaces installed wind and solar capacity as a zero-carbon energy source.

CRESOM still has some shortcomings in its current functions, and future work can be carried out in the following aspects: 1. In terms of temporal accuracy, current computational capabilities limit the depiction of time accuracy to 12-month intervals, making it difficult to capture the hourly fluctuations of renewable energy generation. In the future, the method of typical days can be used to characterize renewable power fluctuations. 2. Regarding spatial resolution, the current computational limitations restrict the spatial resolution to provincial levels. It is difficult to describe the power transmission within the province. In the future, this can be improved by integrating with GIS systems and incorporating actual power grid infrastructure. 3. Regarding infrastructure characterization, there is a limited representation of energy storage technologies other than electrical energy storage. Currently, other forms of energy storage have not been adequately depicted. 4. The model

lacks characterization of the heating system; therefore, in future work, it would be valuable to couple heat supply into the electricity model.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

Nomenclature

t	Time
r	Region
d	Department
e	Energy variety
ee	Different from e 's energy variety

Abbreviations

CRESOM	China Regional Energy Supply System Optimization Model
ED	Energy demand
GDP	GDP growth rate
EIRR	Energy intensity reduction rate
SC	Substitution coefficient
ES	Energy substitution
I_n	Industry
T_r	Transportation
P_o	Power department
NG	Natural gas
CO	Coal
HY	Hydrogen
ELE	Electricity
OI	Oil
CUTCRC	Cumulative unit transition carbon reduction cost
CCS	Carbon capture and storage
WP	Wind power
NG	Natural gas power
NG + CCS	Natural gas power with carbon capture and storage

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