Bulletin of Chinese Academy of Sciences 院刊

Volume 36 | Issue 9 Article 8

9-20-2021

Evaluating Economic and Social Benefits of Accelerated Energy Transition

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Abstract

To achieve carbon neutrality, China's energy system needs a radical transition, and the development of new energy is of central importance. Based on the integrated assessment modeling framework, this study compares economic and social costs and benefits between a scenario reflecting the current energy transition momentum and a scenario of accelerated energy transition. We show that the accelerated energy transition dominated by new energy is essential to achieve carbon neutrality before 2060 and the air quality target required by Beautiful China. The large development of wind and solar power will further reduce their technology costs and the overall energy costs, which will benefit China's wind and solar equipment export and other exporting industries, supporting sustainable economic growth. In addition, the accelerated energy transition will create more jobs and health benefits and avoid substantial social costs of carbon emissions.

Keywords

carbon neutrality; energy transition; new energy; social benefits

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Citation: ZHANG Hongyu, HUANG Xiaodan, ZHANG Da, ZHANG Xiliang. Evaluating Economic and Social Benefits of Accelerated Energy Transition [J]. Bulletin of Chinese Academy of Sciences, 2021 (9): 1039–1048.

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Against the background of carbon neutrality, China should accelerate the radical transition of the energy system to support green and low-carbon development. The low-carbon transition of the energy system will influence the economy, society, environment, and many other aspects. There is, however, no comprehensive assessment on the benefits of accelerating the energy transition in current studies. Therefore, this study analyzes the effects of the current energy system transition and accelerated transition of the energy system on energy consumption cost, economic development, labor employment, and environmental benefits with the integrated assessment modeling framework. This study aims to provide a reference for energy transition under carbon neutrality target in China.

1 Energy transition trend under carbon neutrality

In September 2020, Chinese Chairman Xi Jinping announced at the General Debate of the 75th Session of the United Nations General Assembly, "China will scale up its Intended Nationally Determined Contributions by adopting more vigorous policies and measures. We aim to have CO_2 emissions peak before 2030 and achieve carbon neutrality before 2060." Since China's energy-related carbon emissions account for over 75% of total greenhouse gas emissions [1,2], accelerating the energy transition is critical to achieving carbon neutrality within 40 years.

In March 2021, General Secretary Xi Jinping proposed that one of the key tasks in the future energy field is to "establish a new power system dominated by new energy" at the ninth meeting of the Central Finance and Economics Committee. New energy involves nuclear energy, non-water renewable energy (including wind energy, solar energy, biomass energy, geothermal energy, tidal energy, etc.), and hydrogen energy. In 2019, nuclear energy and renewable energy made up 15.3% of China's energy structure [3], and hydrogen energy made up only about 2% of the end-use energy consumption [4]. Since the power system is the core of the future energy system in China, the establishment of a new power system dominated by new energy reveals that the development of new energy is the key to the transition of China's energy system.

Current studies also indicate that developing new energy is the key to energy transition. DUAN and WANG [5] from the Chinese Academy of Sciences analyzed the impact of the reduction of the global warming-limit target from 2 °C to 1.5 °C on China's emission reduction trajectory, energy structure, and economy with the Chinese Energy–Economy–Environment Integration Model (CE3METL). DUAN from the Chinese Academy of Sciences, ZHOU from Tsinghua University, and other researchers integrated the research results of many other international teams and further evaluated China's technical options to pursue the 1.5 °C warming limit [6]. The *World Energy Outlook 2020* issued by the International Energy Agency also predicted China's energy structure for global sustainable development [2]. XIE et al. from Tsinghua University analyzed the trajectories for achieving the warming-limit target of 2 °C and 1.5 °C in 2050 [7]. Although the above-mentioned studies proposed different opinions on the specific trajectories of China's energy transition, they all suggested developing new energy. However, the above studies mainly focused on the necessity

Supported by: National Natural Science Foundation of China (71690244)

of energy transition, and there lacks systematic analysis on the impact of energy transition on the economy, society, and environment. Therefore, it is necessary to develop an integrated assessment method for energy transition benefits and perform systematic analysis on the impact and cost–benefit of energy transition dominated by new energy.

2 Integrated assessment model for energy transition benefits: methods and assumptions

For the integrated assessment, the cost–benefit assessment is generally conducted by connecting model systems in different fields. Taking the integrated assessment in the field of energy and climate as an example, several studies have quantitatively analyzed and evaluated the economic impact of climate change, emission reduction cost, and health co-benefits by connecting energy economy models with climate models or air quality models [8–11]. The integrated assessment of energy transition benefits can quantitatively analyze the cost–benefit of energy transition by linking energy economy models, air quality models, and health impact models. The cost covers energy consumption costs and economic impact, and benefits cover social-environmental benefits such as the realization of ecological and environmental goals, the promotion of employment, and health.

2.1 Introduction to the integrated assessment modeling framework for energy transition

In order to evaluate the comprehensive benefits of the energy revolution trajectory under carbon neutrality, this study establishes an integrated assessment modeling framework for economic and social benefit evaluation of energy transition; then it couples the power optimization operation model, macro energy economy model, and comprehensive evaluation model of health benefits, and analyzes the influence of different goals and policies on the energy system, economy, cost, employment, and environmental health benefits. The power optimization operation model REPO (Renewable Electricity Planning and Operation) [12] describes the fluctuation of renewable energy, which can optimize the power development goals under emission constraints and calculate the total cost of the power system, thereby estimating the cost input for the development of renewable energy. The macro-economic model C-GEM (China-in-Global Energy Model) [13] and C-REM (China Regional Energy Model), as multi-region, recursive dynamic computable general equilibrium models, can simulate energy development goals under economic, social, and environmental constraints, and evaluate the effects of different energy development goals on the energy industry, overall economy, energy cost, and employment. The comprehensive evaluation model of health benefits REACH (Regional Emissions–Air quality–Climate–Health Model) [14] is a model coupling the air pollutant emission inventory, the atmospheric chemical transmission model, and health benefit evaluation model based on the macro-economic model, which can evaluate the environmental health benefits under different energy development goals.

Fig. 1 shows the coupling relations between the power optimization operation model, macro energy economy model, and comprehensive evaluation model of health benefits. According to the energy development goals under the constraints of economic, social, and environmental development, the carbon emission trajectory of the electric power sector and total power consumption demand in China can be generated by C-GEM model, and then fed back to REPO model as the constraint on carbon emission of the electric power sector and the power demand. REPO model takes minimizing the discounted cost of the power system as the optimization goal, and the installed capacity and power generation capacity of various power generation technologies in each simulation year can be obtained. Furthermore, the national optimal power structure can be fed back to C-GEM model for regulating the power structure in the C-GEM model. Meanwhile, C-GEM model can submit the national carbon emission trajectory to REACH, and simulate the air pollutant emissions. In addition, it can also determine the health effects including morbidity cases and death cases based on the exposure–response relationship, and further identify the corresponding economic impact by virtue of the health impact evaluation form, thus sending the feedback to the C-GEM model. C-REM, a sub-model of REACH, simulates and generates the power demand of each province under the corresponding economic and environmental energy goals, and then sends the feedback to REPO model. Then, REPO model generates the optimal power structure by province, and power import and export scenarios between regions, and sends the feedback to C-REM model for verifying the power structure by province. Simulation feedback and verification are performed several times to ensure that the main coupling parameters of the above models are basically consistent.

2.2 Scenario assumption

Population growth has been identified as an important factor driving economic growth and energy consumption. This study predicts the future population growth trend by reference to the prediction of the medium fertility as stated in the *World Population Prospects 2019* [15] released by the United Nations Department of Economic and Social Affairs (UNDESA): China's population is expected to gradually increase to 1.46 billion and peak by 2030, which will maintain at 1.46 billion in 2035 and decrease to 1.40 billion in 2050. The prospect is also basically consistent with the expected goal of population development in the *National Population Development Plan (2016–2030)*. This study also predicts economic growth by referring to the analysis of mainstream institutions on future economic development. In combination with forecast results of China's economic growth by the World Bank, Organisation for Economic

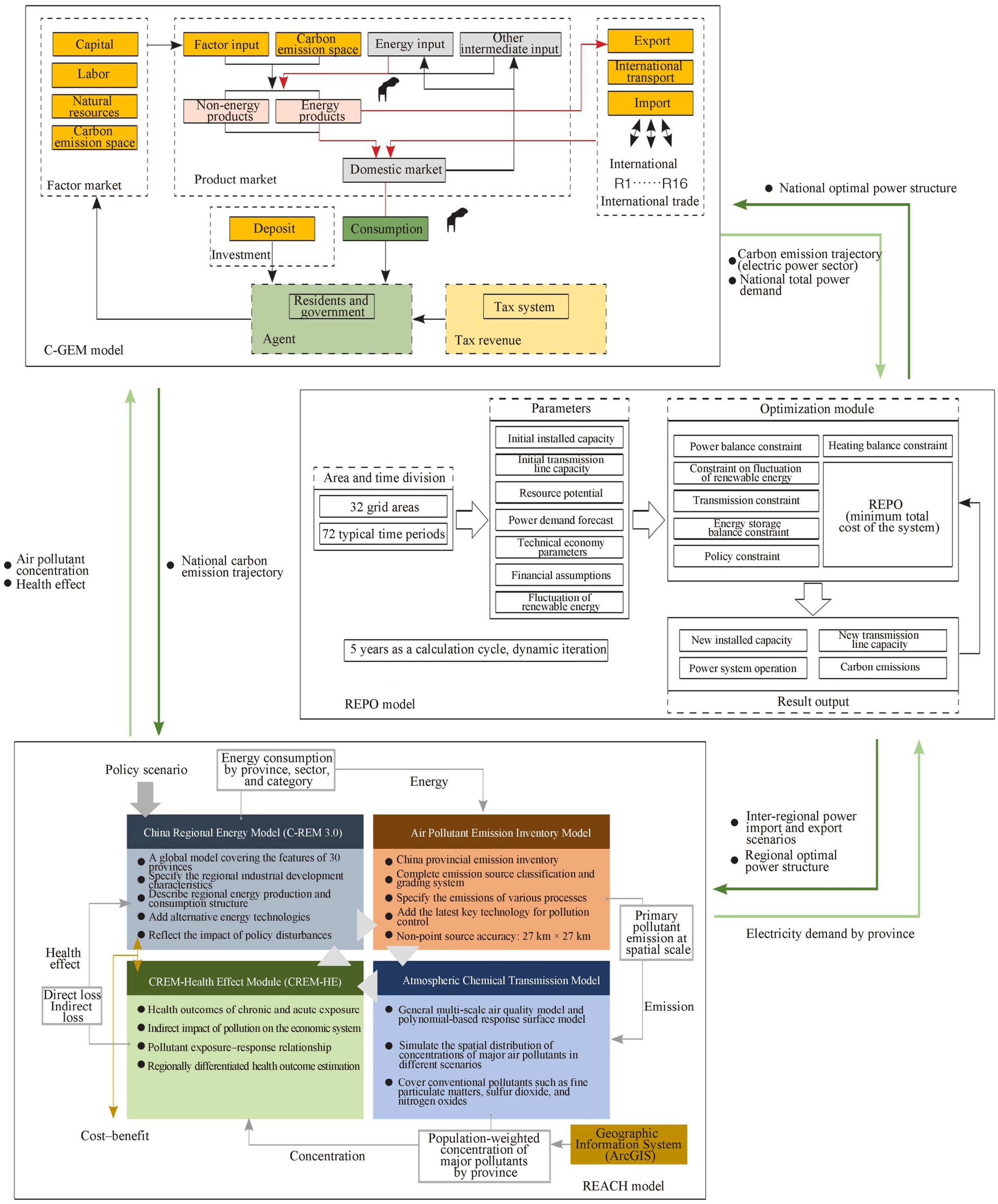

Figure 1 Integrated assessment modeling framework for economic and social benefit evaluation of energy transition

Co-operation and Development (OECD), International Monetary Fund (IMF), US Energy Information Administration (EIA), International Energy Agency (IEA), and Oxford Economics [2,16–20], it is estimated that the average annual growth rate of China's gross domestic product (GDP) will be around 5%–7%, and the long-term average annual growth rate of GDP will slow down. Considering the impact of COVID-19, China's GDP growth rate dropped significantly in 2020 but will rebound with the market recovery. This study predicts that China's economic aggregate will reach USD 30 trillion in 2035 (constant price of USD in 2018), and USD 47 trillion in 2050; GDP per capita will reach USD 21,000 in 2035 and USD 33,000 in 2050.

Since the "12th Five-Year Plan" period, the economic structure in China has changed obviously. The contribution of the industrial sector to the economy has gradually declined, and that of the service industry has increased. Through the analysis of the evolution characteristics of the economic structure of advanced economies, it is expected that the contribution of the industrial sector in the future industrial structure of China will gradually decline, and that of the service industry will gradually increase.

In addition to the above assumptions, this study also studies other key economic and social development goals, and designs conventional and accelerated energy transition scenarios in China (Fig. 2).

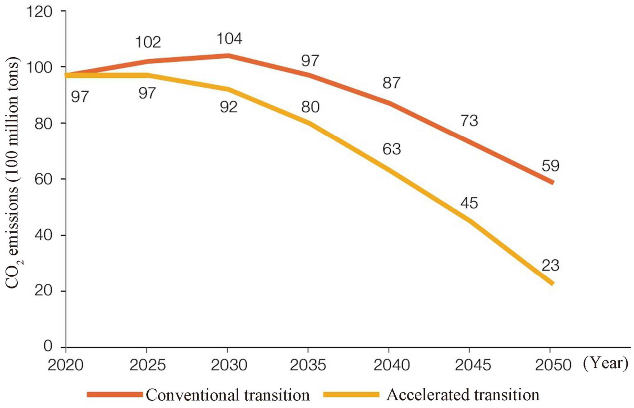

Figure 2 CO_2 emission trajectories under conventional and accelerated energy transition scenarios in China from 2020 to 2050

The conventional energy transition scenario reflects the current policy intensity and energy transition momentum in China. This scenario can achieve nationally determined contributions. It assumes that the emissions reduction efforts will increase after 2030, and the average annual reduction rate of carbon intensity will be 5.3% from 2020 to 2050. This scenario presumes that advanced energy technologies such as hydrogen energy, electric vehicles, and high-efficiency heat pumps will be applied to a certain extent; the level of electrification of end-use energy will be steadily increased, and the cost of wind and solar power generation and energy storage will gradually decline.

The accelerated energy transition scenario reflects the intensity of policies for restraining economic, social, and ecological environment development and energy transition momentum in China. Under this scenario, the carbon emissions generated by fossil energy will decline rapidly after reaching the peak before 2025, and in 2050, it will drop to 25% of the level in 2020. Considering the great challenge of substantial emissions reduction in China, this scenario sets stepped emission reduction targets: the annual reduction rate of the carbon intensity of 5.5% in the "14th Five-Year Plan Period" and the "15th Five-Year Plan Period," 7% from 2030 to 2040, 12% from 2040 to 2050, and 8% from 2020 to 2050. Under this scenario, the transport sector will vigorously promote the application of hydrogen energy and electric vehicles, and the construction sector will strongly promote the application of high-efficiency heat pumps. Consequently, the penetration rate of advanced energy technologies and electrification level of end-use energy are increased evidently, and the cost of wind and solar power generation and energy storage will be further reduced compared with the conventional energy scenario.

3 Integrated assessment of the economic and social benefits of energy transition dominated by new energy

To comprehensively evaluate the economic and social benefits of energy transition, this study simulates and analyzes the effects of the accelerated energy transition on the energy system, economic system, employment, environment & society based on the integrated assessment modeling framework of energy transition. It focuses on evaluating the effects on energy consumption cost, GDP, and other economic factors, and quantifying the social benefits such as co-treatment of carbon and pollution, employment benefits, and health benefits, so as to realize a comprehensive evaluation of energy transition.

3.1 Building a "Beautiful China" under carbon neutrality

In the conventional energy transition scenario reflecting the current energy transition momentum, the proportion of non-fossil energy consumption in China will be significantly increased (32% in 2035 and 53% in 2050), which can realize the goals of 20% in 2030 and 50% in 2050 proposed in the *Energy Production and Consumption Revolution Strategy (2016–2030)* [21]. However, no sufficient efforts have been made under the conventional energy transition scenario. Although energy-related carbon emissions in 2050 will be reduced to 5.9 billion tons from 9.7 billion tons in 2020, there will still be a great gap with the emission reduction required by the carbon neutrality goal in 2060. At the same time, it is hard for some areas to reach the air quality required by "Beautiful China" by 2035, namely annual average $PM_{2.5} < 35\ \mu g/m^3$. Although the annual average $PM_{2.5}$ will be significantly reduced in Tianjin, Anhui, Shandong, Henan, and Hubei by 2035, the values will still be as high as 37, 36, 39, 44, and 38 $\mu g/m^3$, respectively.

To fully realize China's ecological environment development goals, including carbon neutrality by 2060 and air quality requirements of "Beautiful China," the government should further increase the proportion of non-fossil energy in primary energy consumption, such that energy-related carbon emissions will peak around 2025 and then decline rapidly. The proportion of non-fossil energy consumption will be increased to 39% in 2035, and 77% in 2050, which is 24 percentage points higher than that under the conventional energy transition scenario. The reduction of carbon emissions will further improve air quality, and by 2035, all regions in China will achieve the goal of reducing annual average $PM_{2.5}$ below 35 $\mu g/m^3$, and realize coordinated control of CO_2 and $PM_{2.5}$.

3.2 Promoting the reduction of energy consumption cost

In this study, energy consumption cost is mainly calculated based on the average price of coal, petroleum, gas, and electricity consumed by the social end-use sectors, as well as the carbon price determined after the implementation of the national carbon market in the future. Under the conventional energy transition scenario, China's energy consumption cost will be slowly increased from USD 380/ton of standard coal in 2014 to USD 420/ton of standard coal in 2030. The energy consumption cost will decline after 2030 due to the reduced cost of power generation with renewable energy and decreased system cost driven by intelligent and digital technologies. Nevertheless, with the tightening of the constraints on carbon emissions, the growth rate of carbon prices will exceed the decline rate of technical costs, and the energy consumption cost will slightly increase to USD 430/ton of standard coal in 2050 (Fig. 3(a)). Under the accelerated energy transition scenario, energy transition dominated by new energy will further reduce the cost of renewable energy under the impact of policy support and scale economy, and electricity cost will further decline, thereby promoting the continuous decline of energy consumption cost from 2025. As compared with the conventional energy transition scenario, the energy consumption cost under the accelerated energy transition scenario will decline by 2% in 2035, and 16% in 2050, which is lower than the levels in the European Union, the US, Republic of Korea, and other countries and regions (Fig. 3(b)).

As for electricity cost under the conventional energy transition scenario, the Levelized Cost of Energy (LCOE) in 2050 will be 15% lower than that in 2015. Under the accelerated energy transition scenario, the significant increase in the proportion of wind and solar power generation will increase the cost of system consumption. The LCOE, however, will be slightly reduced as compared with the conventional energy transition scenario due to the decline in the cost of power generation with renewable energy and energy storage driven by the scale effect. In specific, the LCOE will drop by 3% in 2035 and 7% and 2050.

3.3 Providing new momentum for economic growth

With the action-forcing of renewable energy development goals and carbon emission constraints, the supply-side structural reform will be further deepened under the accelerated energy transition scenario, and the large-scale development of renewable energy will increase the economic aggregate of China, and achieve green and sustainable economic development. As compared with the conventional energy transition scenario, the GDP under the accelerated energy transition scenario will be increased by about 0.4% in 2035 and about 0.9% in 2050 (Fig. 4).

The decline in LCOE and energy consumption cost due to the reduction of the cost of wind and solar power generation will promote the development of electric vehicles, transportation equipment manufacturing, and other related industries, and contribute to 65% of the above-mentioned GDP growth. Meanwhile, the technological progress and scale effect will further promote the export of China's solar power generation equipment. Under the accelerated energy transition scenario, the added value of export of China's solar energy equipment

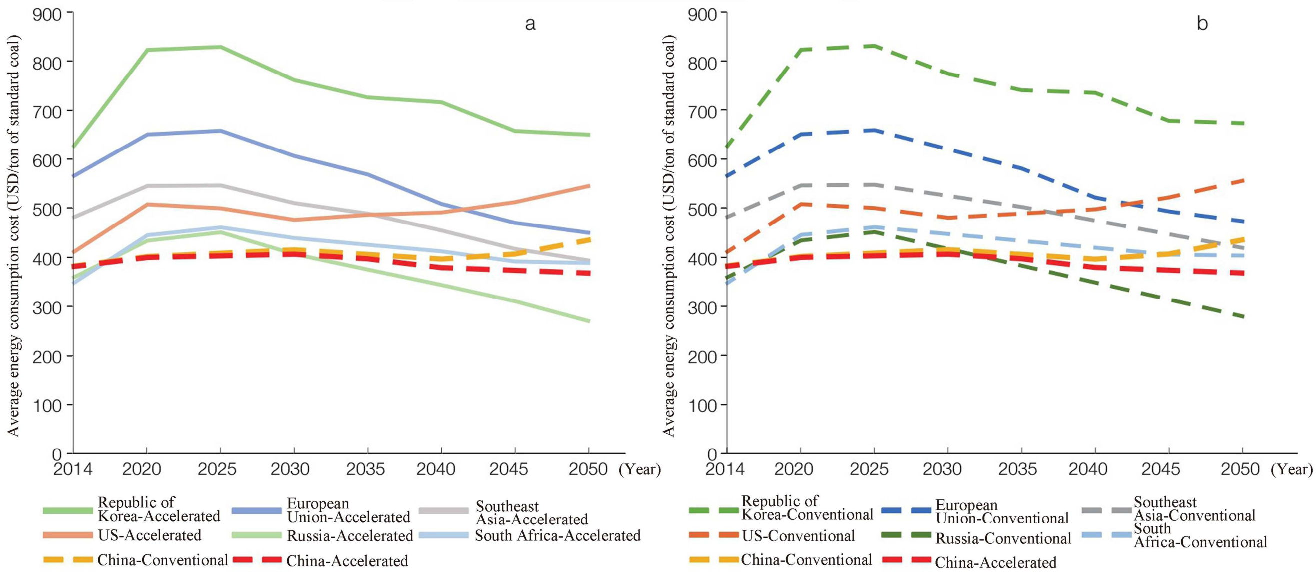

Figure 3 Energy consumption cost in China and other countries and regionsunder conventional (a) and accelerated (b) energy transition scenarios

The average energy consumption cost, including the cost of carbon emission reduction under the operation of carbon market, is calculated using coal equivalent calculation and at the constant price of USD in 2011.

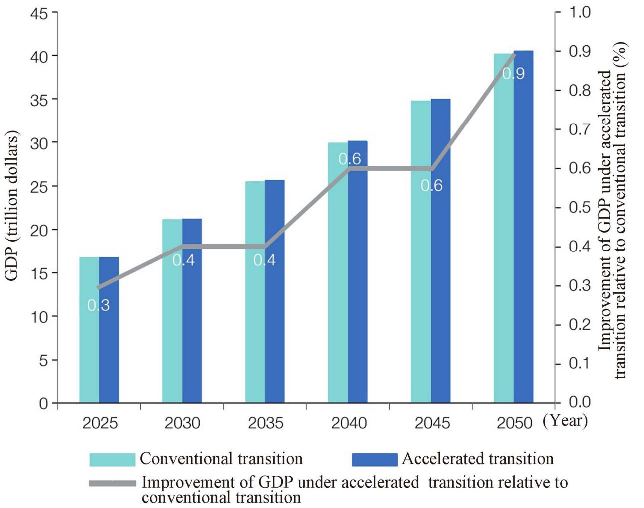

Figure 4 Comparison of gross domestic product under conventional and accelerated energy transition scenarios in China from 2025 to 2050

GDP is calculated at the constant price of USD in 2011.

will increase (the export value will increase from about USD 20 billion in 2019 to USD 120 billion in 2035, and then USD 250 billion in 2050), accounting for roughly 35% of the above-mentioned GDP growth. In addition, the energy transition dominated by new energy will also promote the rapid development of energy internet, hydrogen energy, and energy storage industries, thus becoming the new force supporting economic development and ensuring energy security.

3.4 Effectively increasing employment

The expansion of the scale of the wind power and photovoltaic industries will increase jobs in the related industries. As compared with the conventional energy transition scenario, China's wind power industry under the accelerated energy transition scenario will increase 1.87 million jobs in 2035, most of which will be in the service industry; there will be 17.05 million jobs in 2050, 5 million jobs more than that under the conventional energy transition scenario, and 3 million jobs will be increased in the service industry related to the wind power industry. Under the accelerated energy transition scenario, there will be 10.3 million jobs in the photovoltaic industry in 2035, which is 3 million jobs more than that under the conventional energy transition scenario; it will increase to 19.25 million jobs in 2050, with an increase of 3.7 million jobs compared with the conventional energy transition scenario, most of which will be in the service industry related to the photovoltaic industry (about 2 million).

As for fossil energy-related industries, under the accelerated energy transition scenario, the de-coalification process will be accelerated with the large-scale development of renewable energy. As compared with the conventional energy transition scenario, about 710,000 jobs will be reduced in the fossil energy industry in 2035, including 450,000 in the coal mining and washing industry, and 260,000 in the coal power industry. In 2050, about 1.47 million jobs will be reduced, including 800,000 in the coal mining and washing industry, 500,000 in the coal power industry, and 170,000 in the gas power industry.

The comprehensive comparison indicates that the large-scale development of wind and solar power industry will create more jobs in related industries than the traditional fossil energy industry. Compared with the conventional energy transition scenario, the accelerated energy transition scenario will stimulate the net increase of jobs, i.e., it will increase about 4 million jobs in 2035 and 8 million ones in 2050.

3.5 Bringing environmental and social benefits

The implementation of effective industrial restructuring policies, carbon pricing mechanisms, and pollutant end-of-pipe treatment measures will significantly reduce carbon dioxide emissions, improve air quality, and realize coordinated control of carbon dioxide and $PM_{2.5}$. While achieving carbon neutrality, it is also necessary to make $PM_{2.5}$ reach the national secondary standard (35 $\mu g/m^3$) by 2035. Under the accelerated energy transition scenario, the $PM_{2.5}$ emission, sulfur dioxide emission, and nitrogen oxide emission will drop to about 2.6 million, 5.4 million, and 6.2 million tons in 2035, which are decreased by 59%, 41%, and 55% respectively as compared with the emissions in 2020. In 2050, the $PM_{2.5}$ emission, sulfur dioxide emission, and nitrogen oxide emission will further drop to about 570,000 tons, 960,000 tons, and 1 million tons, which are decreased by 78%, 82%, and 83% respectively as compared with the emissions in 2035.

The large-scale development of renewable energy will improve the air quality, and reduce the premature deaths of residents due to acute and chronic exposure to high concentrations of $PM_{2.5}$. This study takes USD 2 million as the value of a statistical life (VSL) and estimates that the energy transition dominated by new energy will realize health benefits of about USD 200 billion in 2035.

The energy transition dominated by new energy will also avoid social costs caused by a large amount of carbon emissions. The social cost of carbon emission can be used to quantitatively characterize the negative environmental externalities caused by the carbon cycle and climate system of marginal carbon emissions, including but not limited to the impact on productivity, human health, and ecosystems, and property loss caused by frequent extreme weather events. This study takes USD 69, 87, and 105/ton of carbon dioxide as the social cost of carbon emission in 2020, 2035, and 2050, respectively [22,23]. Under the conventional energy transition scenarios, China's social cost of total carbon will increase by USD 190 billion in 2035 as compared with that in 2020, but decrease by around USD 40 billion in 2050 with the decline of carbon emission reduction. Under the accelerated energy transition scenario, China's social cost of total carbon will increase by USD 40 billion in 2035 as compared with that in

2020, but decrease by around USD 430 billion in 2050 due to large-scale reduction of carbon emissions. Compared with the conventional energy transition scenario, the accelerated energy transition scenario can avoid the social cost of carbon emission of about USD 150 billion in 2035 and 400 billion in 2050. Those results indicate the comprehensive economic and social benefits under the accelerated energy transition scenario will be 1% higher of GDP in 2035 and 1.9% higher of GDP in 2050 as compared with the conventional energy transition scenario (Table 1).

4 Summary of economic and social benefits of energy transition and policy suggestions on energy transition

Based on the scenario simulation and comprehensive benefits analysis with the integrated assessment model of economic and social benefits, this study finds that the deep energy transition dominated by new energy is an inevitable choice to achieve carbon neutrality in 2060 and meet the air quality requirements of "Beautiful China." With the rapid decline of the cost of wind and solar power generation and energy storage technology, the deep energy transition dominated by new energy will promote the further decline of energy consumption cost in China, and drive the development of China's manufacturing industry and export of photovoltaic and wind power equipment, thereby stimulating the continuous growth of the economy. The rapid development of new energy will drive the net increase of jobs, and coordinate the control of carbon emissions with emissions of conventional pollutants, bringing obvious environmental health benefits and avoiding social costs caused by large amounts of carbon emissions.

However, it should be noted that the above research results are obtained based on the following hypothesis: "under the accelerated energy transition scenario, the level of electrification will be further improved; the costs of wind power, photovoltaic, and energy storage will decline as compared with the conventional energy transition scenario; the energy system can support a high proportion of new energy." If the above conditions are not met, the final transition benefit will fail to reach the level calculated in this paper. Therefore, it is necessary to increase resource input and policy support in the key fields and encourage various entities to participate in the accelerated energy transition.

(1) Promoting the electrification of end-use sectors to create development space for new energy. The electrification of end-use sectors will improve the utilization efficiency of new energy and increase the power demand, so as to create development space for new energy dominated by electric power. Therefore, it is necessary to develop high-efficient and advanced electrification technologies such as electric vehicles and heat pumps at the demand side, and implement electric energy substitution, in an attempt to improve the level of electrification in end-use sectors.

(2) Developing low-cost new energy and energy storage technologies. High-efficient and low-cost new energy technologies and energy storage technologies are the prerequisites for further reduction of energy consumption costs in China. Therefore, it is favorable to increase R&D investment and policy support in the fields of new energy and energy storage, so as to greatly reduce the cost of new energy and energy storage technologies. The LCOE of wind power and photovoltaic power will drop to about CNY 0.2/kWh in 2035, and that of photovoltaic power will drop to about CNY 0.1/kWh in 2050; the cost of charging and discharging in the energy storage cycle will decrease to about CNY 0.17/kWh (single cycle) in 2035 and CNY 0.1/kWh (single cycle) in 2050.

(3) Establishing an energy system adapting to the large-scale development of new energy. The large-scale development of new energy requires the coordination of energy systems, mechanisms, and systems. The power grid should vigorously develop high-proportion renewable energy grid-connected technology and safe and efficient operation technology for AC/DC hybrid grid, and make breakthroughs in the field of advanced power equipment technology. In addition, it is necessary to further deepen the reform of the power system, and establish a power market mechanism suitable for the participation of a high proportion of new energy.

(4) Strengthening the training of talents in the field of new energy to conform to the development needs of the new energy industry. The large-scale development of new energy should be supported by talents in the related fields. Therefore, efforts should be made to train innovative and technical talents in the fields of new energy technology research and development, new energy engineering application, and new energy system management. Those measures are taken to meet the needs of the development of strategic emerging industries in China and ensure the accelerated transition of energy system.

Table 1 Social cost of carbon emission saved under the accelerated energy transformation scenario

	2025	2030	2035	2040	2045	2050
Social cost per unit of carbon (USD/ton of carbon dioxide, constant price in 2011)	75	81	87	93	99	105
Changes in comprehensive social benefits compared with the conventional energy transition scenario	0.5%	0.8%	1.0%	1.3%	1.4%	1.9%

References

1 United Nations Environment Programme. Emissions Gap Report 2020. Nairobi: United Nations Environment Programme, 2020.

2 International Energy Agency. World Energy Outlook 2020. Paris: IEA, 2020.

3 Department of Energy Statistics, National Bureau of Statistics. China Energy Statistical Yearbook 2020. Beijing: China Statistics Press, 2021. (in Chinese)

4 China Hydrogen Alliance. White Paper of Hydrogen Energy and Fuel Cell Industry in China. Beijing: People's Daily Press, 2021. (in Chinese)

5 Duan H B, Wang S Y. From 2 °C to 1.5 °C: China's Challenges to Attain the Global Warming-limit Targets. Management World, 2019, 35 (10): 50–63. (in Chinese)

6 Duan H B, Zhou S, Jiang K J, et al. Assessing China's efforts to pursue the 1.5 °C warming limit. Science, 2021, 372: 378–385.

7 Writing Group of project comprehensive report. Comprehensive report on China's Long-term Low-carbon Development Strategy and Transformation Path. China Population, Resources and Environment, 2020, 30 (11): 1–25. (in Chinese)

8 Yang Z L. Strategic Bargaining and Cooperation in Greenhouse Gas Mitigations: An Integrated Assessment Modeling Approach. Cambridge: The MIT Press, 2008.

9 Moore F C, Diaz D B. Erratum: Temperature impacts on economic growth warrant stringent mitigation policy. Nature Climate Change, 2015, 5 (3): 280.

10 Dong H J, Dai H C, Dong L, et al. Pursuing air pollutant co-benefits of CO_2 mitigation in China: A provincial leveled analysis. Applied Energy, 2015, 144: 165–174.

11 Cai W J, Hui J X, Wang C, et al. The Lancet Countdown on $PM_{2.5}$ pollution-related health impacts of China's projected carbon dioxide mitigation in the electric power generation sector under the Paris Agreement: A modelling study. The Lancet Planetary Health, 2018, 2(4): e151–e161.

12 Yang Y Z, Zhang H Y, Xiong W M, et al. Regional power system modeling for evaluating renewable energy development and CO_2 emissions reduction in China. Environmental Impact Assessment Review, 2018, 73: 142–151.

13 Huang X D, Chang S Y, Zheng D Q, et al. The role of BECCS in deep decarbonization of China's economy: A computable general equilibrium analysis. Energy Economics, 2020, 92: 104968.

14 Zhang X, Ou X M, Yang X, et al. Socioeconomic burden of air pollution in China: Province-level analysis based on energy economic model. Energy Economics, 2017, 68: 478–489.

15 Department of Economic and Social Affairs, United Nations. World Population Prospects: The 2019 Revision. New York: Department of Economic and Social Affairs, United Nations, 2019.

16 World Bank. Global Economic Prospects, June 2020. Washington, DC: World Bank, 2020.

17 Organisation for Economic Co-operation and Development. Interim Economic Outlook Forecasts. Paris: OECD, 2020.

18 International Monetary Fund. World Economic Outlook. Washington, DC: IMF, 2020.

19 Energy Information Administration. Annual Energy Outlook 2019. Washington, DC: EIA, 2019.

20 Oxford Economics. World economy. Economic Outlook, 2020, 44 (3): 33–35.

21 National Development and Reform Commission, National Energy Administration. Energy Production and Consumption Revolution Strategy (2016–2030). [2021–01–09]. http://www.gov.cn/xinwen/2017-04/25/ 5230568/files/286514af354e41578c57ca38d-5c4935b.pdf. (in Chinese)

22 US Government Inter-Agency Working Group. Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866. [2020-12-11]. https://www.epa.gov/sites/default/files/2016-12/documents/sc_co2_tsd_august_2016. pdf.

23 Rennert K, Kingdon C. Social Cost of Carbon 101, A review of the social cost of carbon, from a basic definition to the history of its use in policy analysis. Washington, DC: Resources for the Future, 2019.

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