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Renewable Energy Development Planning Combining LEAP Simulation and Techno-Economic Optimization

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ABSTRACT

The Chinese government has pledged to peak carbon emissions by 2030 in response to climate change. As a relatively large and fast-growing renewable energy source, it is important to explore the development path of the wind and solar power to achieve a low-carbon transition. In this paper, we use Long-range Energy Alternatives Planning System (LEAP) to simulate energy consumption and carbon emissions in China. The learning curve model characterizes the relationship between renewable energy technology maturity and installed market size. In this study, four scenarios with eight sub-scenarios are constructed. The results show that early and appropriate increases in investment in wind power and PV can help accelerate the technology maturity and the reduction of technology costs which will bring long-term benefits. Meanwhile, the appropriately accelerated wind power and PV development planning can effectively reduce the carbon peak level and cumulative carbon emissions.

Keywords: Technology maturity, Renewable energy, Path planning, LEAP

NONMENCLATURE

Abbreviations	
LCOE	levelized cost of energy
Symbols	
C_1	the cost to produce the first product
X	cumulative production
b	learning rate index
CI	total cost
$\mathrm{Ele}_{\mathrm{coal,n}}$	the cost of thermal power generation in year n
$\mathrm{CAPEX}_{\mathrm{pv,n}}$	initial investment of PV in year n
$\mathrm{CAPEX}_{\mathrm{wind,n}}$	initial investment of wind power in year n
$\mathrm{OPEX}_{\mathrm{pv,n}}$	O&M cost of PV in year n
$\mathrm{OPEX}_{\mathrm{wind,n}}$	O&M cost of wind power in year n
r	discount rate

1. INTRODUCTION

In order to control the rate of global temperature rise and mitigate the harm caused by climate change, countries around the world signed the Paris Agreement, which set the goals of no more than 2°C and 1.5°C temperature rise. As a major emitter, China accounts for 28% of the world's total carbon emissions in 2019[1]. In response to international climate policies, China has pledged to achieve carbon peaking by 2030 and carbon neutrality by 2060.

At the national level, researchers have studied the carbon reduction pathways in China, including the time reaching carbon peaking and the amount of carbon peaking under different scenarios [2]. At the provincial level, researchers have explored the carbon peaking pathways of different types of cities and the impact of cross-provincial trade on regional emissions[3][4][5]. At the industry level, researchers have also studied the carbon reduction potential of different sectors in China and the corresponding emission reduction pathways, using sectors as entry points[6][7].

Renewable energy plays a pivotal role in China’s low carbon transition. The researcher explores the relationship between carbon emissions from renewable energy operations and capital-related carbon emissions, urbanization and renewable energy demand[8], and assesses the impact of renewable energy on carbon emissions in China[9].

In the process of technology development, the technology maturity will be influenced by the market. The current study focused on how the arrangement of renewable energy may actualize the development of a low-carbon route in China. However the influence of market growth on the development of renewable energy technology was overlooked. The installed market

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influences the maturity of renewable energy technologies such as wind power and PV. The LEAP model is used to simulate the national energy use and the carbon emission level in our work. The learning curve model is used to characterize the impact of installed market capacity on the maturity of wind and solar power. The long-term economic development of wind power and PV is planned by a nonlinear optimization model, which considers the impact of market dynamics on the future cost of renewable power generation. Meanwhile, the optimization results will be fed back to LEAP to evaluate the energy use and carbon emissions of the optimized power mix. In this study, four scenarios and eight sub-scenarios are constructed to explore the technology development planning under the policy constraint of carbon peaking in 2030. The research structure of this paper is shown in Fig.1.

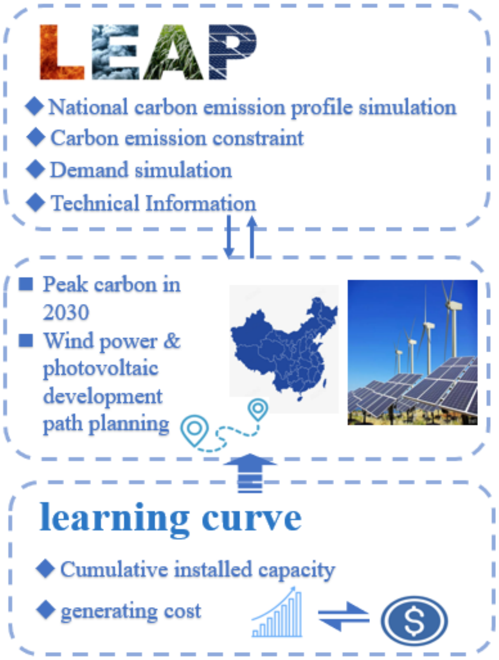

Fig.1 Research structure

2. METHODOLOGY

2.1 *National Carbon Emissions Simulation*

In this paper, the LEAP model is used to simulate the energy use and carbon emissions in China by considering the sectors of agriculture, forestry and fishery, industry, construction, transportation, wholesale and retail, etc. The carbon emissions are calculated by the end-use consumption, fuel use of each industry and the emission factors for each fuel.

2.2 *Technology Maturity Development Simulation*

Technology maturity is strongly related to the market development of the technology, and this study uses a learning curve model to characterize the relationship between technology maturity and the market. The traditional learning curve model represents the relationship between the total production and the cost of production, as shown in Equation 1[10].

$$C_x = C_1 \times X^{-b} \tag{1}$$

where C_x denotes the cost of producing the product x, C_1 denotes the cost of producing the first product, X denotes the cumulative production, and b denotes the learning rate index.

The extreme efficiency model indicates that when the production process enters the standardization stage, the development of technological progress slows down, and the rate of cost reduction tends to level off, as shown in Equation 2[10].

$$C_x = A + C_1 \times X^{-b} \tag{2}$$

where A is the standard cost to produce the product. At present, wind power and PV have entered a relatively mature stage of development, and it is more appropriate to use the ultimate efficiency model.

2.3 *Development path optimization of Wind and solar power*

In this study, the economic assessment is evaluated as an objective function of the wind and solar power development planning, which includes coal cost, the initial investment cost of wind power and PV, the O&M cost of wind power and PV, as shown in Equation 3

$$\begin{aligned} CI = \min \sum_{n=1}^{N} (&Ele_{coal,n} + CAPEX_{pv,n} \\ &+ CAPEX_{wind,n} \\ &+ OPEX_{pv,n} \\ &+ OPEX_{wind,n})/(1+r)^n \end{aligned} \tag{3}$$

where $Ele_{coal,n}$ denotes the cost of coal power generation in year n, $CAPEX_{pv,n}$ denotes the initial investment of PV in year n, $CAPEX_{wind,n}$ denotes the initial investment of wind power in year n, $OPEX_{pv,n}$ denotes the O&M cost of PV in year n, $OPEX_{wind,n}$ denotes the O&M cost of wind power in year n, and r denotes the discount rate.

3. SCENARIO SETTINGS

According to the national policy, in the baseline scenario (B), the total energy consumption within 6 billion tons of standard coal by 2030, the proportion of natural gas reaching about 15%, the carbon emissions per GDP decreasing by more than 65% compared to 2005, and achieving the carbon peaking target no later than 2030. Based on the baseline scenario, policy scenarios of wind strengthening (W), PV strengthening (P), and mixture strengthening of wind power & PV (M) are set as the first-layer scenarios used to explore the impact on wind power and PV technology development under different electricity consumption levels.

This study includes wind power, photovoltaic, nuclear power, hydropower, coal power, and other power generation types. The focus of this study is to plan wind and solar power development. Hence the development levels of nuclear, hydropower, and the other power generation types remain consistent in each scenario and are not reflected in the discussion. The power generation share below is the share of wind power, solar power, and coal power.

In order to explore the development of wind power and PV installations under different market installation constraints, this study set up the additional second-layer market sub-scenarios NP, W2P5, and W3P6. Under each first-layer scenario, the sub-scenario NP represents the planning without further optimizing wind and solar power development. In the further optimization sub-scenario W2P5, the allowable annual installed capacity of wind power and PV ranges from 20 to 40 million kW and 50 to 85 million kW. In the sub-scenario W3P6, the allowable annual installed capacity of wind power and PV ranges from 30 to 50 million kW and 60 to 95 million kW.

4. RESULT AND DISCUSSION

The data used in this study are from the National Energy Administration, International Renewable energy Agency (IRENA) and International Energy Agency (IEA). The learning curve of wind power and PV is obtained by fitting the installed capacity and LCOE data over the years, as shown in Fig.2.

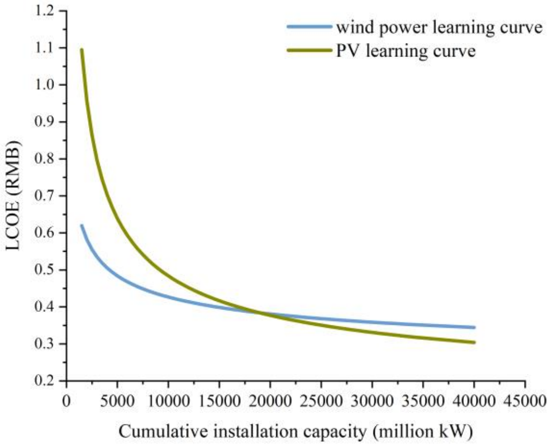

Fig.2 Learning curve

The LCOE decline levels for wind power and PV under different market installation constraint scenarios are shown in Fig.3. The LCOE reduction of PV is more than wind power from 2022 to 2035.

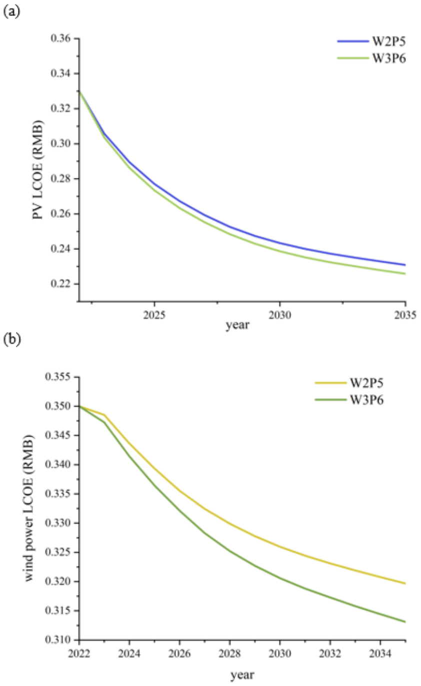

Fig.3 Wind power LCOE and PV LCOE

Total cost is an important indicator in evaluating wind and solar power development. The total costs of W2P5 and W3P6 are RMB 26865.05 billion and RMB 26825.07 billion, respectively under the baseline scenario. Under the wind strengthening scenario, the total cost of W2P5 and W3P6 is RMB 28966.9 billion and RMB 28927 billion, respectively. Under the PV strengthening scenario, the total cost of W2P5 and W3P6 is RMB 26824.1 billion and RMB 26784.1 billion, respectively. Under the wind power & PV strengthening scenario, the total cost of W2P5 and W3P6 is RMB 26824 billion and RMB 26784 billion, respectively. The sub-scenario W3P6 has lower total project costs than the sub-scenario W2P5 under different scenarios, which implies that appropriately accelerated wind and solar power investments can accelerate technology maturity and effectively reduce total project costs.

Fig.4 depicts the difference between various wind and solar power installation planning under baseline scenario in the generation mix. In the sub-scenario W2P5 under baseline scenario, coal power accounts for 53.9% in 2035, as shown in Fig. 4(a). In the sub-scenario W3P6 under baseline scenario, coal power accounts for 46% in 2035 as shown in Fig. 4(b). In 2035, the coal power accounts for 53.7%, 53.9%, and 53.9% in sub-scenario W2P5 under wind power strengthening scenario, the PV strengthening scenario, and the wind power & PV strengthening scenario, respectively. The coal power in 2035 accounts for 45.7%, 46%, and 46% in sub-scenario W3P6 under the wind power strengthening scenario, the PV strengthening scenario, and the wind power & PV strengthening scenario, respectively. By comparing the development of wind power and PV under different sub-scenarios, it is easy to find that appropriately accelerated investment in wind power and PV can effectively promote a low-carbon transformation of the power structure.

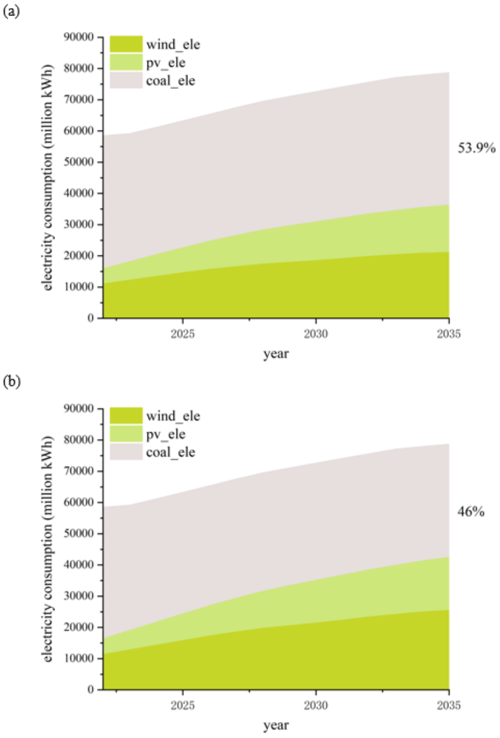

Fig.4 Power generation for sub-cases W2P5 and W3P6 under the baseline scenario

According to the simulated by LEAP, the baseline scenario, wind power strengthening scenario, PV strengthening scenario, and wind power & PV strengthening scenario all achieve carbon peak in 2030 at 12.3 billion tons, 12.2 billion tons, 12 billion tons, and 11.9 billion tons, respectively, as shown in Fig.5.

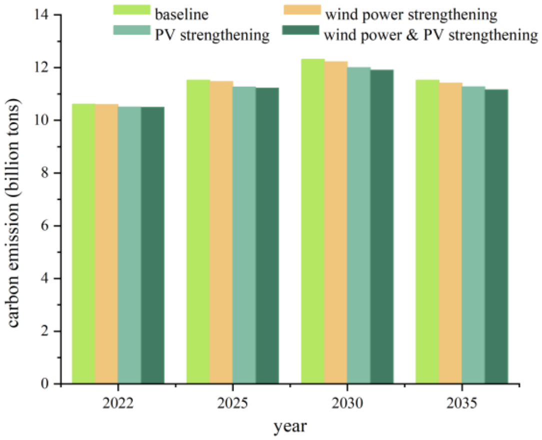

Fig.5 Carbon emissions for the four scenarios

According to the simulation results, all scenarios achieve carbon peaks in 2030. Under the baseline scenario, W2P5 and W3P6 achieve carbon peaks at 11.212 billion tons and 10.854 billion tons, respectively, 8.9% and 11.8% lower than scenario NP, as shown in Fig.6(a). Under the PV strengthening scenario, the W2P5 and W3P6 peaks of carbon are 11,207 million tons and 10,848 million tons, respectively, which are 6.6% and 9.6% lower than scenario NP, as shown in Fig. 6(b). Under the wind power strengthening scenario, the W2P5 and W3P6 peaks are 11,367 million tons and 11,030 million tons, 6.99% and 9.75% lower than scenario NP, respectively, as shown in Fig. 6(c). Under the wind power & PV strengthening scenario, W2P5 and W3P6 peak at 11,207 million tons and 10,848 million tons, respectively, 5.88% and 8.9% lower than the NP scenario, as shown in Fig.6(d).

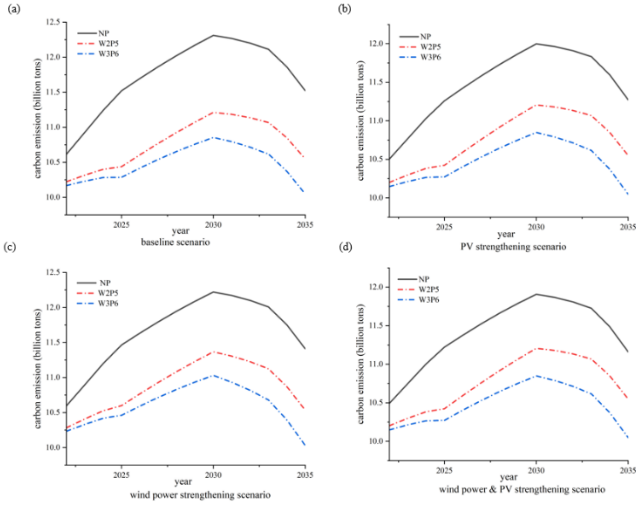

Fig.6 Annual Carbon Emissions

The cumulative carbon emissions for 2022-2035 under each scenario are shown in Fig.7.

Among the four scenarios, the cumulative carbon emissions of the sub-scenario NP under wind power & PV strengthening scenario are the lowest, at 159.8 billion tons, which is 2.8% lower than the sub-scenario NP under baseline scenario. The sub-scenario NP under the PV strengthen scenario and the wind power strengthening scenario are 2.2% and 0.6% lower than the sub-scenario NP under the baseline scenario, respectively. The sub-scenario with the lowest cumulative carbon emissions in each scenario is W3P6, and the sub-scenario W3P6 decreases by 10.7%, 8.8%, 9.1%, and 8.2% compared to sub-scenario NP under the baseline scenario, PV strengthening scenario, wind power strengthening scenario and wind power & PV strengthening scenario respectively. The sub-scenario W3P6 decreased by 8.3%, 6.3%, 6.8%, and 5.7%, respectively, compared with sub-scenario NP under the baseline scenario, PV strengthening scenario, wind power strengthening scenario and wind power & PV strengthening scenario respectively.

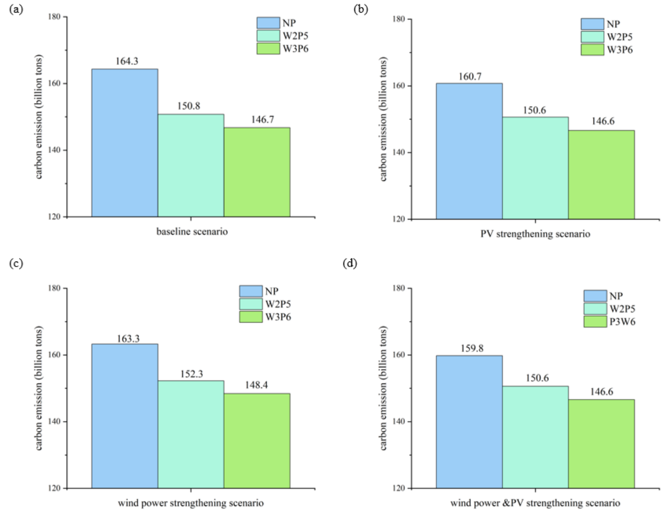

Fig.7 Cumulative Carbon Emissions

5. CONCLUSIONS

This study uses a learning curve model to characterize the relationship between installed wind power capacity and technology maturity, as well as simulates the energy use and national carbon emission through LEAP. An optimization model that takes the dynamic change of market development to technology maturity into account is used to optimize the economic optimal development planning of wind power and PV. The results show that an early and appropriate increase in wind power and PV investment can help accelerate technology development and reduce future technology costs, thus realizing long-term benefits. At the same time, the initial investment cost can be covered by the economic benefits brought by the technology maturity at a later stage, making the lower total cost. Appropriately accelerated wind and solar power development paths can lead to a cleaner electricity mix that can reduce peak carbon emissions at a lower economic cost. Meanwhile, appropriately accelerated wind and solar power development planning can lead to lower cumulative carbon emissions and reduce the cost of carbon emission reductions needed to achieve carbon neutrality by 2050.

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