Energy Proceedings
Vol 31, 2023
ISSN 2004-2965

Evaluating the Cost Impacts to Meet China's Renewable Electricity Portfolio Standard Target in 2030

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ABSTRACT

The power sector plays a pivotal role in China's carbon peak and carbon neutrality targets. To build a low-carbon power system, it is important to develop wind and solar. This study aims to evaluate the economic impacts of the newly launched renewable portfolio standard in 2030 in China using a cost minimization model and an input-output model. The results show that to accomplish the renewable electricity portfolio standard in 2030, the installed wind and solar capacity will have to reach 1451.9 gigawatts (GW) in 2030. The Northeast, Northwest, and North regions will deploy the most installed capacity, and Inner Mongolia will take on the most renewable energy generation tasks. The annual cost of wind and solar development is expected to be 506.6 billion yuan in 2030, 94.7% of which are new construction costs and storage costs. Renewable energy growth will result in a 5.4-cent (RMB) per kWh rise in the national average electricity price compared to 2019, and Heilongjiang, Gansu, and Shanxi are the most affected. The rapid development of renewable electricity in the next decade will increase the Consumer Price Index (CPI) by 0.4%, Producer Price Index (PPI) by 0.9%, and Gross Domestic Product (GDP) deflator by 0.5% in 2030. Based on the results, we propose to improve the electricity market mechanisms, enhance the electricity transmission stability, and develop policies appropriate to local conditions.

Keywords: renewable energy, regional deployment, macro-impact, cost minimization

NOMENCLATURE

Abbreviations	
RPS	Renewable Portfolio Standard
PV	Photovoltaics
NEA	National Energy Administration
CPI	Consumer Price Index
PPI	Producer Price Index
GDP	Gross Domestic Product
NDRC	National Development and Reform Commission
CNY	Chinese Yuan

1. INTRODUCTION

Global warming is one of the greatest threats to the world, and many countries are trying to reduce CO_2 emissions. China, the largest emitter, committed to achieving carbon peak by 2030 and carbon neutrality by 2060. Decarbonization of the power sector plays a crucial role in achieving carbon neutrality for two reasons. First, the power sector accounts for more than 40% of the total CO_2 emissions in China. Second, a feasible path for other major emitting sectors such as transportation, industry, and buildings to accomplish the neutrality goal is to accelerate the electrification [1]. To build a low-carbon power system, it is important to increase the proportion of renewable energy generation by wind and solar photovoltaics (PV) in the coming decades. In December 2020, it was announced that China will boost its installed capacity of wind and solar to more than 1200 GW by 2030 (Fig. 1).[1] This means that China's installed wind and

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[1] Source: NPC deputies suggest measures to reach China's carbon neutrality goal- China.org.cn

solar capacity will grow by an average of at least 74 GW per year from 2021 to 2030.

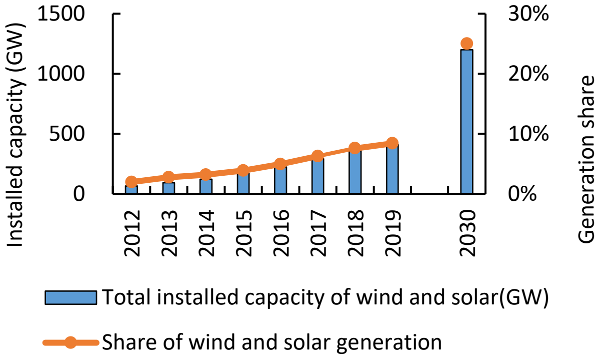

Fig. 1. The installed capacity and generation of wind and solar (Data Source: China Electricity Council)

To accelerate the development of renewable energy, the National Development and Reform Commission (NDRC) and the National Energy Administration (NEA) released the Renewable Portfolio Standard (RPS) in 2020. Minimum targets for the share of non-hydro renewable electricity (mainly wind and solar PV) in the total electricity consumption for individual provinces were issued, with the targets ranging from 3.5% to 20% by the end of 2020 (NDRC and NEA 2020). The electricity sellers and industrial users that are unable to meet the minimum renewable electricity consumption requirement can either purchase green certificates or purchase renewable consumption quotas directly from companies that have met the minimum requirement and have surplus quotas. This new policy prioritizes renewable energy in electricity generation, promotes direct trading, and encourages the consumption of renewable energy across provinces. Provincial governments are responsible for developing renewable electricity consumption plans to meet the RPS target set by the central government. They need to trade off developing their own renewables or buying from other provinces.

China's RPS policy is expected to boost the development of wind and solar as well as incur significant costs for several reasons. First, the intermittency, randomness, and variance features of wind and solar need to be accompanied large scale deployments of electricity storage. Second, the distribution of wind and solar resources concentrates in the North and West of China, which is far from the electricity consumption provinces in the Central and South China. There will be much more inter-provincial trade to meet the RPS target, which leads to the construction of transmission lines. Additionally, the costs will be passed on to customers in the form of higher electricity prices. Electricity is an important input of production and living, and the cost will have an inflation effect on the economy and society through the price transmission mechanism. To cope with the impact of the increasing share of renewable electricity on the economic development and people's lives, it is necessary to assess the cost of renewable electricity development and its economic and social impact.

In addition, where to invest in renewable energy and to what extent need to be considered from a forward-looking perspective[2]. The power industry is highly capital-intensive, and once built, it creates a "lock-in" effect on the electricity generation mix for decades. Changes in the determining factors need to be considered when deploying wind and solar power, which not only include the resource endowment but also the electricity demand. The electricity demand of different provinces will evolve with the changes in population, economy, and economic structure.

This study first uses a panel regression model to estimate the electricity demand and then constructs a cost minimization model to optimize the regional deployment of wind and solar units in China in 2030, with the constraint of meeting the 2030 non-hydro RPS by province. Based on the regional deployment of units, we calculate the costs required to meet the 2030 RPS target. Then, we use the input-output model to measure the macroeconomic impact of increases in the electricity price resulting from the development of wind and solar.

We estimate that the new installed capacity of wind and solar in 2020–2030 is 1037.6 GW and the cumulative installed capacity is 1452.9 GW in 2030. Regions choose between purchasing electricity and building renewable energy units based on resource endowment, transmission cost, and other factors. Northwest and Northeast have the largest cumulative installed capacity in 2030 with 313.8 GW and 300.1 GW, respectively, accounting for 21.6% and 20.7% of the cumulative installed capacity in China, followed by the North, East, Central, and South regions, with the South accounting for 10.5%. To meet the 2030 non-hydro RPS, the average annual cost is estimated to be 506.6 billion yuan from 2021 to 2030. Most of the cost comes from the new capacity construction (45.5%) and energy storage construction (49.1%). This cost will increase the national average electricity price by 5.4 cents (RMB) per kWh and make the Consumer Price Index (CPI), Producer Price Index (PPI), and Gross Domestic Product (GDP) deflator increase by 0.4%, 0.9%, and 0.5%.

Our paper relates to the literature in several ways. One line of related studies is about the cost of increasing the share of renewable energy. Jaquelin et al. (2015) proposed the concept of economic carrying capacity, which provides an evaluation framework for the high proportion of renewable energy consumption. They believe that the main reason affecting the high proportion of renewable energy consumption is economic factors rather than technical factors[3]. Heptonstall and Gross (2021) systematically reviewed the international evidence of the cost and impact of integrating wind and solar energy into the electricity grid. They found that the cost was very small or even negligible if the share of wind and solar power was low. When the share increased, the cost increased significantly. This part of the cost mainly depended on the cost of the flexible operation of the system[4]. Compared with these previous literature, our study assesses the cost of renewable energy development in China under the RPS target in 2030 and estimates the macroeconomic impact of the cost rather than just a qualitative analysis.

We also examine some literature on quota allocation. Some scholars began to discuss the total target and realization path of RPS. Based on the MESSAGE model, Chen et al. (2008) simulated the impact of different incentive policies on the development path of energy technology to establish the provincial renewable energy planning[5]. Yi, Xu, and Fan (2017) built a multi-regional optimization model to simulate the implementation path of a renewable energy electricity quota system under different policy targets[6]. In addition to the allocation of renewable energy, some scholars have studied the allocation of quotas regarding other areas, such as carbon emissions[7-11] and energy consumption[12, 13]. In contrast to previous papers examining renewable energy quotas, this paper estimates the wind and solar units by region. Previous papers more often just estimated renewable energy consumption under the quota system.

This paper is based on a cost minimization perspective for optimization. Some models of renewable energy target decomposition based on the perspective of cost provide important references. Wei and Rose (2009) proposed a regional energy-saving quota allocation scheme under transactions based on cost minimization[14]. Lamy et al. (2016) decomposed the cost of wind into installation cost, operation cost, and transmission cost and then measured the economic benefits of a wind farm built in load centers or resource centers by the cost minimization method[15].

The main contributions of this paper are as follows. First, we combine an econometric model and a cost-minimization model to forecast the total capacity of installed wind and solar and their regional deployment to meet China's RPS target in 2030, which takes into account the dynamic changes in economic size, structure, and population among provinces. These quantitative results can provide both central and local policy makers as well as investors with information on the investment potentials and gaps and help them make informed decisions. Second, we estimate the associated costs of wind and solar development in the next ten years and measure the economic and social impact of these costs. Decarbonizing the electricity system requires massive new investment in storage and transmission lines. Since electricity is an important input factor in production, these costs could be passed through to end users and inflate the general price level. Our study will help governments and enterprises prepare for the possible increase in electricity prices brought about by achieving carbon peak and carbon neutrality.

The remainder of the paper is structured as follows. Section 2 provides the analytic methodology and data description, Section 3 presents our results, and Section 4 concludes.

2. METHODOLOGY AND DATA

2.1 Conceptual framework

To estimate the development of wind and solar power in China in 2030, it is first necessary to estimate the electricity demand in China in 2030. We construct a panel regression model to measure the effects of economic development, population, industrial structure, etc. on electricity demand. Then, the electricity demand forecast is multiplied by the non-hydro RPS targets to

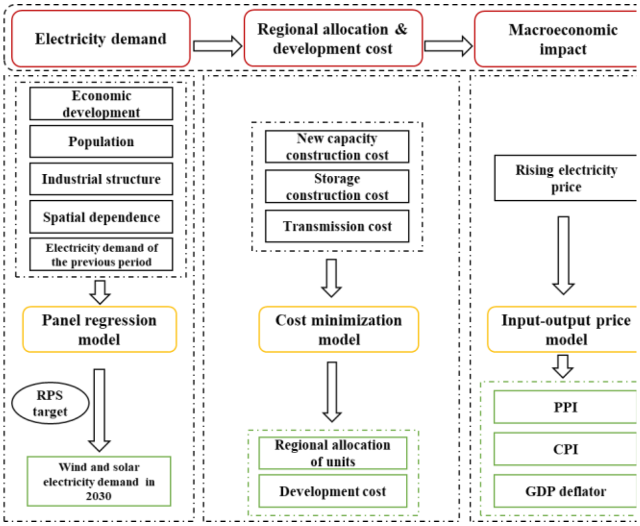

Fig. 2. The conceptual framework

obtain the non-hydro renewable electricity demand of each province.

Based on non-hydro renewable electricity demand forecasting, we construct a cost minimization model to obtain the wind and solar installed capacity regional deployment in 2030. Then, we can obtain the wind and solar development costs, including new capacity construction cost, energy storage construction cost, and transmission cost.

Finally, we use the input-output model to measure the macroeconomic impact of the increase in electricity price resulting from the development of wind and solar, as reflected in the changes in the CPI, PPI, and GDP deflator. The research framework is shown in Fig. 2.

2.2 Electricity demand panel regression model

The demand for renewable electricity in each region is determined by the total electricity demand and the non-hydro RPS targets, as shown in Eq.(1).

$$RD_i = ED_i \beta_i \tag{1}$$

where RD_i is the non-hydro renewable electricity demand in region i, ED_i is the annual electricity demand in region i, and β_i is the non-hydro RPS target in region i.

Given the RPS targets, to estimate the demand of non-hydro renewable electricity, we need to forecast the electricity demand in 2030. We construct a panel regression model to measure the relationship between electricity demand and each influencing factor. Referring to Ehrlich and Holdren (1971), economic development, population, and industrial structure are the main characteristics of electricity demand[16]. The selected explanatory variables include GDP per capita, population size, the share of electricity demand in the secondary industry, electricity demand in the previous period, and the spatial dependence in each province. (1) GDP per capita is a key indicator to measure the economic development of a region. Regions with higher economic development tend to have a higher electricity demand. (2) Population is another important factor affecting electricity demand. Electricity is important in people's daily lives, and there is a positive relationship between the population size and the electricity demand. (3) The share of the secondary industry in GDP is an indicator to measure the structure of electricity consumption. Since 1980s, the proportion of electricity consumption in the secondary industry in China has been maintained at over 70%, and it directly affects the growth of electricity consumption in the whole society. It is difficult to obtain the electricity consumption of each province by industry in a long time series, so we use the share of the secondary industry in GDP instead. (4) The spatial dependence is also considered to indicate the correlation between electricity demand in neighboring provinces, reflecting the spillover effects of technology, economy, capital, etc. between regions[17]. (5) Electricity demand of the previous period has an important impact on the forecast of the current period. It takes time for a large-scale electricity infrastructure to increase and decrease, and electricity consumption of the previous period can reflect the construction of the electricity infrastructure. In the absence of large external shocks, electricity demand tends to have small fluctuations based on the previous period.

The general model is

$$\begin{aligned}\ln(ED_{it}) &= \eta_i + f(GDP_{it}) + \pi_i \ln(ED_{it-1}) \\ &+ \rho \sum_{j=1}^{k} w_{ij} \ln\left(ED_{j,t-1}\right) + Z_{it}\delta + \varepsilon_{it}\end{aligned} \tag{2}$$

where i and t represent provinces and time, ED_{it} measures electricity demand, GDP_{it} is per capita gross domestic product, and $f(\cdot)$ is a generic flexible functional form allowing for a potentially non-linear non-monotonic emissions income relationship. To capture the potentially heterogeneous speed of adjustment in capital replacement, we include one-period province specific lagged dependent variables in the initial specification. $\sum_{j=1}^{k} w_{ij} \ln\left(ED_{j,t-1}\right)$ represents the spatial dependence. We construct a rook contiguity weight matrix to measure the impact of the previous year's electricity demand in k neighboring provinces on the current year's electricity demand in province i. w_{ij} are the weights of the impact given to the previous year's electricity demand by its k neighboring provinces. Z_{it} is a vector of exogenous variables, which vary across time and provinces (including population size and the share of the secondary industry). η_i is a province fixed effect including differences in electricity demand between provinces due to climate differences, local customs, etc. These differences do not change over time. Considering the effect of the time factor on electricity demand, we consider both forms of adding a time trend term and adding a time fixed effect. ε_{it} is a stationary ergodic error term. π_i and ρ are scalars, and δ is a vector of parameters.

2.3 Regional deployment model

The distribution of natural resources varies greatly in China. Based on nationwide cost minimization, renewable energy installations will be prioritized in areas with better endowments of wind and solar energy resources. For regional decision-makers, the goal is to meet the non-hydro RPS targets in 2030 with minimal cost, and the choice is whether to build new wind and solar installations in the region or to purchase renewable electricity from other regions. In terms of regional division, we first divide the country into six regions based on electricity grids: Northeast, North, Central, East, Northwest, and South regions, as shown in Fig. 3. Then, the regional installed capacity is allocated to each province.

Fig. 3. Regional division

We conduct the cost minimization objective among different regions to obtain the optimal values of wind and solar capacity deployment. The cost components include the construction cost of the new installed capacity, storage construction cost, transmission cost, etc. The cost minimization objective function is shown in Eq.(3).

$$\mathrm{Cost} = CC + GC + SC + TC \tag{3}$$

The cost minimization objective function is subject to two constraints. The first constraint is that the sum of the new installed capacity in each region is equal to the national new installed capacity target, as shown in Eq.(4). Based on meeting the RPS targets, the national new installed capacity target is adjusted at the interval of 1000 MW. The national total installed capacity of wind and solar is set to continue the stock ratio of 1:1 in 2019. The second constraint is the balance of electricity supply and demand in each region. The renewable electricity demand in 2030 has been given in section 3.1. The renewable energy demand in the net electricity output region is equal to the electricity generation minus the outgoing power, and the renewable energy demand in the net electricity input region is equal to the electricity generation plus the purchasing electricity, as shown in Eq.(5) and Eq.(6).

$$\textstyle\sum_i \sum_c Cap_{i,c} = Totalcap_c \tag{4}$$

$$RD_j = \sum_c \left(Cap_{j,c} + Oldcap_{j,c}\right) hour_{j,c} - \sum_i^M DV_{j.i} \tag{5}$$

$$RD_i = \sum_c \left(Cap_{i,c} + Oldcap_{i,c}\right) hour_{i,c} + \sum_j^N DV_{j,i} \tag{6}$$

Eq.(7) to Eq.(10) present the components of the total cost.

Eq.(7) is the calculation method of the construction cost of the new installed capacity. The construction cost is the unit construction cost multiplied by the new installed capacity. The operational lifetime of wind and solar installations is assumed to be 25 years, and the construction cost of the new installed capacity in the model is shared equally each year.

$$CC = \sum_i \sum_c Cap_{i,c} \times \frac{FC_{i,c}}{L} \tag{7}$$

Eq.(8) is the calculation method of the electricity generation cost for renewable electricity. The total generation cost is equal to the total installed capacity multiplied by the marginal generation cost. We assume that the marginal generation cost of solar and wind is ignored.

$$GC = \sum_i \sum_c \left(Cap_{i,c} + Oldcap_{i,c}\right) \times hour_{i,c} \times GC_{i,c} = 0 \tag{8}$$

Eq.(9) is the calculation method of the storage construction cost. Wind and solar generation are intermittent. As the proportion of wind and solar generation increases, storage construction is essential. The storage technologies are divided into pumped storage, compressed air storage, and electrochemical storage, of which electrochemical storage is the main choice for future large-scale construction. Referring to provincial standards, we assume that new wind and solar plants need to be equipped with no less than 10% of storage facilities.

$$SC = \sum_i \sum_c \left(Cap_{i,c} + Oldcap_{i,c}\right) \times 10\% \times SC_i \tag{9}$$

Eq.(10) is the calculation method of the transmission cost. The national transmission cost is equal to the sum of the regional transmission costs.

$$\mathrm{TC} = \sum_i \sum_j \sum_c TC_{j,i} \times DV_{j,i} \tag{10}$$

Table 1 shows the explanation of variables in the cost minimization model.

Based on regional deployment, two approaches can be used for realizing the provincial deployment of installed capacity targets within the region: integration capacity index and environmental pressure index. The integration capacity index is designed based on each province’s capacity to integrate wind and solar power.

Because of the intermittency, randomness, and variance features of wind and solar power, provinces with more thermal and hydropower can provide more ancillary capacity to coordinate the integration of wind and power. The environmental pressure index is designed based on the environmental pressure faced by each province, and usually the provinces with developed industries will have a stronger demand for emission reduction, which will also have a greater demand for wind and solar power generation. The detailed description of the index is provided in the APPENDIX A.4.

2.4 Input-output price model

This paper uses the input-output price model to analyze the inflationary effects (i.e., the changes in CPI, PPI, and GDP) caused by the increase in the electricity cost. This paper only gives a brief description of the model in APPENDIX A.2. More methodological details can be found in Miller and Blair (2009) and Chen et al (2019)[18, 19].

2.5 Data description

Data are collected from various sources. The non-hydro RPS targets, installed capacity, and generating hours of wind are collected from the National Energy Administration. Information on the generating hour of solar and the construction cost of solar and wind are collected from the BJX electricity website. Information on transmission lines is collected from the National Development and Reform Commission. The GDP, electricity consumption, and population size are from the National Bureau of Statistics. It is assumed that China's industrial structure will not change significantly from 2018 to 2030. Due to the impact of COVID-19, some data in 2020 are not representative, so many data are based on 2019. The detailed parameter setting and calculation methods are shown in APPENDIX A.3.

3. RESULTS

3.1 Regional deployment of wind and solar units

3.1.1 Electricity demand forecasting results

After a specification search over a large space of models, we choose the optimal model for forecasting. The explanation of the model selection is in APPENDIX A.1. The forecasted electricity demand by provinces in 2030 is shown in Fig. 4. The total electricity demand is 9.4 trillion kWh in 2030. The electricity demand is large in the east and relatively small in the west.

Table 1
The explanation of variables in the cost minimization model

Variable	Variable meaning
i, j	Region
c	Installed capacity type (c= wind, solar)
$Cost$	The annual total cost of non-hydro renewable electricity generation
$Cap_{i,c}$	New capacity of installed capacity c in region i in the next decade
CC	The construction cost of the new installed capacity in China
GC	Electricity generation cost of non-hydro renewable electricity in China
SC	Storage construction cost in China
TC	Non-hydro renewable electricity transmission cost in China
$FC_{i,c}$	Unit equipment and installation cost of installed capacity c in region i
L	Operation life [1]
$Oldcap_{i,c}$	Built capacity of installed capacity c in region i in 2019
$hour_{i,c}$	Average annual generating hours of installed capacity c in region i
$GC_{i,c}$	Unit generation cost of installed capacity c in region i
SC_i	Unit storage construction cost of region i
$TC_{j,i}$	Unit transmission cost from region j to region i
$DV_{j.i}$	Output electricity from region j to region i
$Totalcap_c$	National new installed capacity target
RD_i	Non-hydro renewable electricity demand in region i
M	Number of electricity output regions
N	Number of electricity input regions

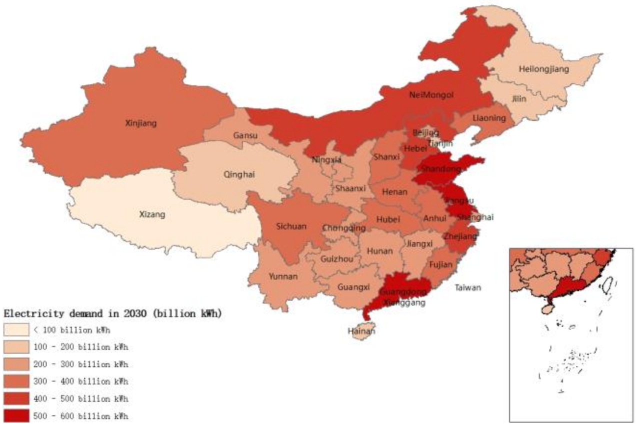

Fig. 4. Estimated electricity demand by provinces in 2030

3.1.2 Regional deployment

It is estimated that the national demand for non-hydro renewable electricity in 2030 will be 2479.9 billion kWh. Also, the national non-hydro renewable electricity consumption proportion is estimated to be 26.4% in 2030. The national wind and solar installed capacity will reach 1.5 billion kW, an increase of 250.4% over 2019. Also, the estimated value exceeds the total capacity target of 1.2 billion kW proposed by China at the Climate Ambition Summit.[2]

Table 2 shows the regional deployment of non-hydro renewable energy installation. As shown in Fig. 5, under the constraint of the non-hydro RPS, the new installed capacity is mainly distributed in the Northeast, Northwest, and North regions. The result is consistent with the wind and solar endowment of each location, which makes the result convincing. There are almost no differences in the installation construction costs and storage construction costs between regions, and the main differences that cause the different renewable energy installations are generating hours and transmission costs. The Northwest and Northeast regions have great advantages in power generating hours.

The proportion of the new installed capacity in the Northeast region is the largest. Among the electricity input areas, North accounts for the largest proportion of the new installed capacity. To a certain extent, this result is due to the higher demand for electricity in the North region. To meet the RPS targets, they need to build more renewable energy plants in addition to purchasing electricity. The generating hours of wind and solar in the South and East regions are low, and the cost is high if they rely too much on the self-development of renewable energy. Therefore, they are more likely to choose to purchase electricity. In addition to the cost factor, the high proportion of the renewable energy

Table 2
New and cumulative installed capacity by region in 2030 (unit: GW)

Region	New installed capacity (2020-2030)				Cumulative installed capacity			
	Wind	Solar	Total	Proportion	Wind	Solar	Total	Proportion
North	97.0	81.7	178.7	17.2%	140.3	125.4	265.7	18.3%
East	149.0	0.0	149.0	14.4%	168.3	43.6	211.8	14.6%
Central	156.6	0.0	156.6	15.1%	179.6	29.0	208.6	14.4%
Northeast	0.0	230.4	230.4	22.2%	50.1	250.1	300.1	20.7%
Northwest	0.0	209.6	209.6	20.2%	53.6	260.2	313.8	21.6%
South	113.3	0.0	113.3	10.9%	134.1	17.7	151.8	10.5%
SUM	515.9	521.6	1037.6		726.0	725.9	1451.9	

Table 3
Cross-region transmission（unit: billion kWh）

		Net input area					
	Electricity transmission	Central	East	South	North	SUM	Share of output electricity in electricity generation
Net output area	Northeast	53.7	31.3	15.0	42.5	142.6	28.6%
	Northwest	30.4	8.0	0.0	19.2	57.5	12.6%
	SUM	84.0	39.3	15.0	61.7	200.1	
	Share of purchased electricity to consumed electricity	18.6%	9.0%	4.4%	12.4%		

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[2] Source: https://www.un.org/zh/climatechange/climate-ambition-summit

capacity is related to the high RPS targets of these regions and the task of transmitting electricity outward.

3.1.3 Cross-region transmission

Fig. 5 shows the cross-region transmission of non-hydro renewable electricity in 2030. According to our prediction, the North, Northeast, and Northwest regions will still be the core area of wind and solar generation in China in 2030, undertaking about 60% of the renewable energy electricity generation in China. Among the renewable electricity transmission areas, the Northeast region is the most important one, and its electricity transmission accounts for 28.6% of the electricity generation. The outward electricity transmission in the Northwest region is 57.5 billion kWh, accounting for 12.6% of its electricity generation. The Central region is the largest renewable electricity net input area. Its purchased electricity accounts for 18.6% of the total consumption. This is largely due to its proximity to areas rich in wind and solar resources and low transmission costs, so it chooses to purchase a large amount of electricity. Table 3 shows the transmission of non-hydro renewable electricity between regions.

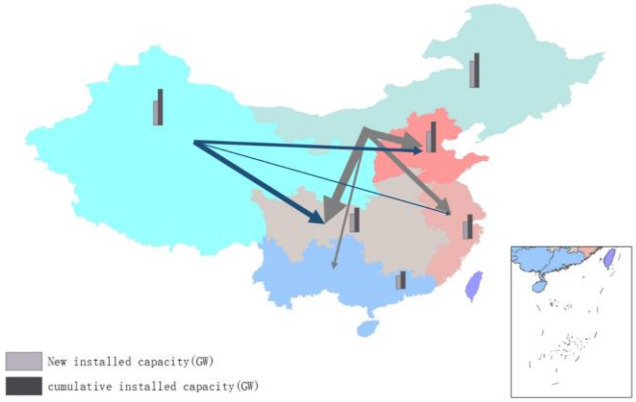

Fig. 5. Regional deployment and cross-region transmission of wind and solar in 2030

3.1.4 Provincial deployment

The overall difference between the integration capacity index and the environmental pressure index is small. The provinces with more thermal power and hydropower capacity generally have resources, land, and other elements to develop renewable energy and undertake more renewable electricity supply tasks. Therefore, in the following analysis, we choose the deployment results of the consumption capacity index to carry out the specific analysis among provinces, and the results based on the environmental pressure index are shown in APPENDIX A.4. The results are shown in Fig. 6. Inner Mongolia, Shandong, Xinjiang, and Jiangsu are the 4 provinces with the largest number of new installed capacity. The newly installed wind and solar capacity of Inner Mongolia is 117.3 GW compared with that in 2019, accounting for 11.3% of the total new installed wind and solar capacity in China.

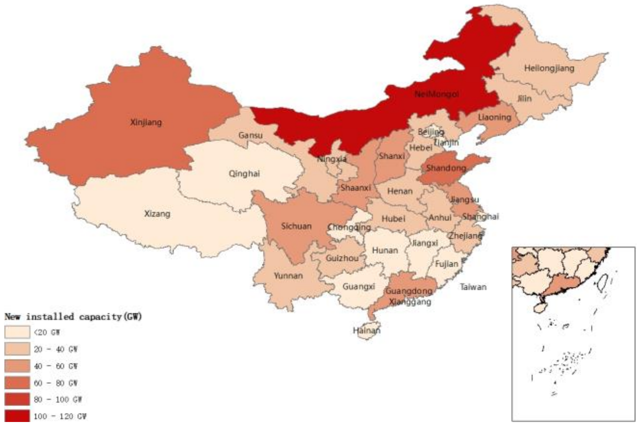

Fig. 6. The provincial new installed capacity of wind and solar in 2030

3.2 *Development cost of wind and solar power*

Under the national non-hydro RPS target (26.4%), the annual cost of wind and solar development is expected to be 506.6 billion yuan in 2030. Fig.7 shows the cost structure of wind and solar development. The unit cost of ancillary services increases with the increase in renewable energy. Most of the cost comes from the new capacity construction cost (45.5%) and storage construction cost (49.1%). The new transmission line is not considered, and the transmission cost accounts for 5.3%.

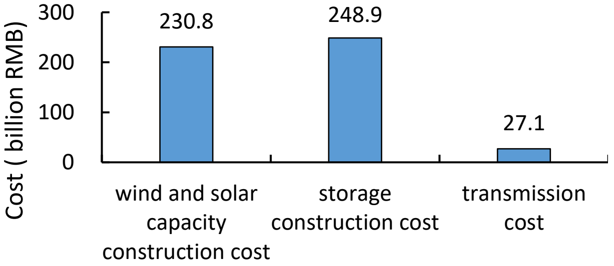

Fig. 7. Cost structure

3.3 *Macroeconomic impact*

3.3.1 Electricity price change

The rising proportion of renewable electricity consumption will lead to the rise in electricity consumption costs. When the non-hydro RPS target is increased to 26.4% in 2030, the national average electricity price will increase by 5.4 cents (RMB) per kWh. In the regional electricity price setting, the principle is "who uses electricity, who bears it". The electricity input area should bear part of the installation and storage cost of the electricity output area and transmission cost. Table 4 shows the rise in electricity prices by region in 2030 due to the increased share of renewable electricity consumption. Electricity prices in the Central, North, and Northeast regions increase the most because of their high RPS targets or large amounts of purchased electricity. Although the RPS target is also high in the Northeast region, it already has a lot of current wind and solar capacity, so the rise in electricity price is relatively small. The South has the lowest increase in price due to its lowest renewable electricity consumption share.

Table 4

Average electricity price increase in regions (unit: cent in RMB per kWh)

Region	Average electricity price increase
North	5.9
East	4.8
Central	6.0
Northeast	5.9
Northwest	4.7
South	4.3
Nationwide	**5.4**

The impact of the rise in electricity prices varies between provinces. Because the income levels vary between provinces, the sensitivity to electricity prices is also different. We designed an index to measure the impact. This index is equal to the increase in electricity prices divided by GDP per capita, as shown in Eq.(11). The higher the index, the greater the impact of carbon neutrality on people's lives and economic development. As shown in Fig. 8, the electricity price increase has the greatest impact on Heilongjiang, Gansu, Shanxi, and Hebei, while the impact is less on the eastern provinces.

$$\sigma = \frac{Average\ electricity\ price\ rise}{GDP\ per\ capita} \tag{11}$$

3.3.2 Inflation effects

The increase in electricity cost caused by the increase in the renewable electricity consumption ratio will have an inflation effect on the economy and society with the price conduction mechanism. We use the input-output price model to analyze the inflation effect of the electricity price increase under different consumption ratios and use the changes in the Consumer Price Index (CPI), Producer Price Index (PPI), and GDP deflator to measure the impact of electricity price changes on consumption activities, production activities, and the whole national economy. According to the model, the rapid development of renewable energy in the next decade will cause the CPI, PPI, and GDP deflator to increase by 0.4%, 0.9%, and 0.5% in 2030, indicating that the electricity price increase caused by the increasing proportion of renewable electricity consumption has a greater impact on production than on consumption.

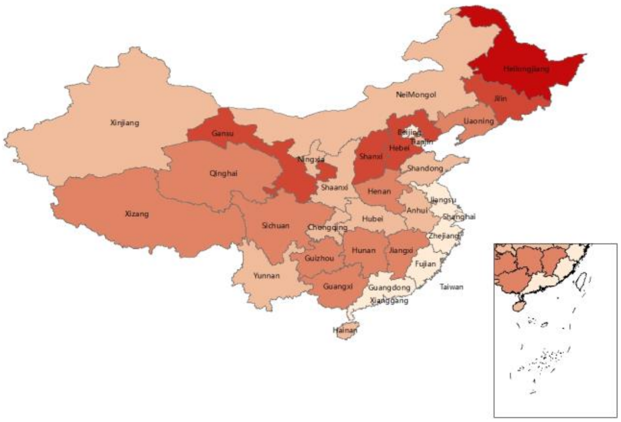

Fig. 8. The impact of electricity price increase on the provinces (Note: The darker the color, the greater the impact of carbon neutrality on the provinces)

4. CONCLUSIONS AND POLICY IMPLICATIONS

4.1 Conclusions

We forecast that the national non-hydro renewable electricity demand in 2030 will be 2480 billion kWh, accounting for 26.4% of the national electricity demand. The North and Central regions have the highest demand of 495.9 billion kWh and 452.2 billion kWh, accounting for 20.0% and 18.2% of the national demand, respectively, while the South region has the lowest demand, accounting for 13.7% of the national demand. To meet these demands, the total new installed capacity of wind and solar in 2020-2030 is 1037.6 GW, and the cumulative installed capacity is 1452.9 GW in 2030.

Due to the regional variation in the demand and supply factors among the regions, the regional distribution of wind and solar deployment vastly differs. The Northeast and Northwest have the largest new installed capacity from 2020 to 2030 with 230.4 GW and 209.6 GW, respectively, accounting for 22.2% and 20.2% of the new installed capacity in China, followed by the North, Central, East, and South regions, with the South accounting for 10.9%. The cumulative installed capacity of wind and solar is in the order of Northwest, Northeast, North, East, Central, and South regions. At the provincial level, Inner Mongolia, Shandong, and Xinjiang have more new installed capacity, and these provinces are all rich in renewable resources.

We also find that the total inter-regional trade does not change much, and thus, there is no need for a large scale of new transmission lines. To meet the RPS target, the Inter-regional non-hydro renewable electricity trade will increase to 200.1 billion kWh in 2030, mainly from the Northeast and Northwest regions to other regions.

The annual cost of wind and solar development in 2030 is estimated to be 506.6 billion yuan. Most of the cost comes from the new capacity construction (45.5%) and storage construction (49.1%). The transmission cost is relatively small, accounting for 5.3%. Currently, new wind and solar power plants in China require supporting energy storage facilities. As technology advances, the technology cost of wind and solar power will predictably decrease, but the cost of energy storage facilities remains high, which makes the storage cost higher than the wind and solar capacity construction cost under the RPS target.

Implementing the RPS will result in the increase in the electricity cost for the whole society. We estimate that the national average electricity price will rise by 5.4 cents in RMB by 2030 compared to 2019, and the prices in the Central, North, and Northeast regions will rise the most. The Eastern provinces are more insensitive to the electricity price increase, while people and enterprises in Heilongjiang, Gansu, and Shanxi are more affected by the rise in electricity prices. The electricity price increase will have an impact on the whole national economy, with the CPI, PPI, and GDP deflator increasing by 0.4%, 0.9%, and 0.5% in 2018, and the impact on production is greater than that of the residents' consumption.

4.2 Policy implications

The development of renewable energy represented by wind and solar is very important for the realization of carbon neutrality. However, the cost brought by its rapid development will impact the national economy. Combined with the results, we propose several policy suggestions from the following aspects.

First, it is important to reduce the cost of energy storage to mitigate the cost impacts of the RPS because it accounts for the largest share of the cost of achieving the RPS target. Energy storage is playing an increasingly important role in the development of wind and solar power. In addition, the development of renewable energy is closely related to land availability, resource distribution, taxation policy, etc., resulting in a large number of non-technical costs, such as land costs and taxes. The non-technical cost cannot be accurately accounted for but is not negligible. Reducing the non-technical cost is also important in the development of renewable energy.

Second, cost-effectively integrating renewable energy relies on a larger balancing area and the market mechanism. In order to achieve cost minimization, provinces need to trade electricity through the market. We need to not only engage renewable electricity in the market but also create a national market that allows electricity to be traded nationwide. In the process, there may be an imbalance in the distribution of benefits and costs, so some provincial governments may be reluctant to build the national market. It is important to balance inter-provincial interests and resolve inter-provincial barriers for the national electricity market.

REFERENCE

[1] He G, Lin J, Sifuentes F, Liu X, Abhyankar N, Phadke A. Rapid cost decrease of renewables and storage accelerates the decarbonization of China's power system. Nat Commun. 2020;11:2486.

[2] Yi BW, Eichhammer W, Pfluger B, Fan Y, Xu JH. The spatial deployment of renewable energy based on China's coal-heavy generation mix and inter-regional transmission grid. Energ J. 2019;40:45-74.

[3] Jaquelin C, Paul D, Bethany S, Mackay M. Grid integration and the carrying capacity of the U.S. grid to incorporate variable renewable energy. National Renewable Energy Laboratory. 2015.

[4] Heptonstall PJ, Gross RJK. A systematic review of the costs and impacts of integrating variable renewables into power grids. Nat Energy. 2021;6:72-83.

[5] Chen R, Zhang XL, He JK, Yue L. Provincial level renewable energy planning based on the MESSAGE model. J Tsinghua Univ (Sci & Tech). 2008;48:1525-1528. (in Chinese)

[6] Yi BW, Xu JH, Fan Y. Optimal pathway and impact of achieving the mid-long term renewable portfolio standard in China. J of Systems Engineering. 2017;32:312-324. (in Chinese)

[7] Bohringer C, Welsch H. Contraction and convergence of carbon emissions: An intertemporal multi-region CGE analysis. J Policy Model. 2004;26:21-39.

[8] Wei C, Ni J, Du L. Regional allocation of carbon dioxide abatement in China. China Economic Review. 2012;23:552-65.

[9] Yu S, Wei Y-M, Wang K. Provincial allocation of carbon emission reduction targets in China: An approach based on improved fuzzy cluster and Shapley value decomposition. Energy Policy. 2014;66:630-44.

[10] Zhang YJ, Wang AD, Da YB. Regional allocation of carbon emission quotas in China: Evidence from the Shapley value method. Energy Policy. 2014;74:454-64.

[11] Miao Z, Geng Y, Sheng JC. Efficient allocation of CO_2 emissions in China: A zero sum gains data envelopment model. J Clean Prod. 2016;112:4144-50.

[12] Zhang LX, Feng YY, Zhao BH. Disaggregation of energy-saving targets for China's provinces: Modeling results and real choices. J Clean Prod. 2015;103:837-46.

[13] Guo J, Zheng XY, Wei C. Disaggregating energy use cap among China's provinces. J Clean Prod. 2016;127:374-86.

[14] Wei D, Rose A. Interregional sharing of energy conservation targets in China: Efficiency and equity. Energ J. 2009;30:81-111.

[15] Lamy JV, Jaramillo P, Azevedo IL, Wiser R. Should we build wind farms close to load or invest in transmission to access better wind resources in remote areas? A case study in the MISO region. Energy Policy. 2016;96:341-50.

[16] Ehrlich PR, Holdren JP. Impact of population growth. Science. 1971;171:1212-1217.

[17] Giacomini R, Granger CWJ. Aggregation of space-time processes. J Econometrics. 2004;118:7-26.

[18] Chen ZM, Chen PL, Ma ZM, Xu SY, Hayat T, Alsaedi A. Inflationary and distributional effects of fossil energy price fluctuation on the Chinese economy. Energy. 2019;187:115974.

[19] Miller RE, Blair PD. Input-output analysis: Foundations and extensions. 1st ed. London: Cambridge University Press;2009.

[20] Auffhammer M, Carson RT. Forecasting the path of China's CO_2 emissions using province-level information. J Environ Econ Manag. 2008;55:229-47.

[21] Lin YF. Justin Yifu Lin on China's Economy. 1st ed. Beijing: CITIC Press Group; 2021.

APPENDIX

A.1 Estimation methods and model selection for electricity demand

To measure the impact of various factors on electricity demand, we refer to the panel regression model constructed by Auffhammer and Carson (2008)[20]. Compared with time series regression forecasting, panel regression can expand the sample size and provide greater degrees of freedom. In addition, panel regression contains information from both cross-sectional and time series dimensions and, thus, reflects the impact of regional development differences on electricity demand.

To select a forecasting model, we use a specification search over a large space of models. Within this framework, we favor the Bayes/Schwarz information criterion (BIC) as our model selection criterion to select between non-nested models and break path dependence. This selection criterion favors a more parsimonious model specification compared to the Akaike information criterion (AIC), adjusted R^2 or R^2, because it punishes the inclusion of additional parameters more heavily.

Table A1 lists estimation results from a set of benchmark models as well as the “best models” according to AIC/BIC and R^2.

As can be seen from Table A1, the adjusted R^2 of all six groups of models is above 90%, which indicates that all six groups of models have a good fit. Also, the population size and the share of the secondary industry have positive effects on the change in electricity consumption. This is consistent with our expectations in the selection of variables. $\ln(GDP)^2$ has a negative impact, indicating that electricity consumption may decrease after a higher degree of economic development. Especially under the current situation in which China's population has a low or even negative growth rate, it is possible that China's electricity consumption will be in that situation in the coming decades. Compared with model 2, model 3 adds the electricity consumption of the previous period, and the adjusted R^2 is increased to 99%. Also, the AIC and BIC values are reduced to about -2000, which shows that the power consumption of the previous period has a very strong explanatory power for the current period. So, the inertia of electricity consumption is a factor that must be considered in the forecast. Model 4 and model 5 add year fixed effects and time trend terms, respectively, with the same other variables, and the results show that the year trend term is not significant in model 5 and the AIC and BIC of model 4 are lower than those of model 5, indicating a preference for considering the effect of time from year fixed effects based on the AIC and BIC criteria. Model 6 considers spatial dependence, but its result is insignificant, indicating that electricity consumption is less subject to spatial dependence and is a full local rigid demand. Models 4 and 5 include year fixed effects and time trend terms, respectively, and the result shows that the year trend term of model 5 is insignificant. Collectively, model 3 and model 4 have the best fit, and model 4 lacks two variables of population size and secondary industry share compared to model 3. In predicting the electricity consumption of each province in 2030, the values of the corresponding explanatory variables need to be predicted. The error in the prediction of electricity consumption will be larger as more explanatory variables are predicted. We follow the principle of making the explanatory variables streamlined with a good model fit. Also, based on the criteria of AIC and BIC, model 4 has a better fit on the forecast. Therefore, we choose model 4 as the optimal model for forecasting.

Table A1
Selected estimation results from the specification search

lnED	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
ln(GDP)	0.340**	1.526*	0.463***	0.210**	0.395***	0.233**
	(0.152)	(0.759)	(0.114)	(0.078)	(0.083)	(0.100)
Ln(GDP)^2		-0.064	-0.024***	-0.009**	-0.019***	-0.010**
		(0.040)	(0.006)	(0.004)	(0.004)	(0.005)
ln(IS)	0.736***	0.685***	0.117**			
	(0.181)	(0.208)	(0.045)			
ln(P)	0.846**	1.226**	0.174***			
	(0.401)	(0.529)	(0.062)			
$\ln(ED_{i,t-1})$			0.895***	0.941***	0.932***	0.941***
			(0.038)	(0.031)	(0.031)	(0.031)
ln year		109.337***	14.840**		0.274	
		(31.198)	(6.403)		(3.207)	
$\sum_{j=1}^{k} w_{ij} \ln(ED_{j,t-1})$						-0.002
						（0.003）
Constant	-3.346	-843.007***	-115.603**	-0.722*	-3.605	-0.822
	(3.661)	(237.072)	(48.325)	(0.399)	(24.336)	(0.493)
Province FE	YES	YES	YES	YES	YES	YES
Year FE	YES	NO	NO	YES	NO	YES
adj. R^2	0.940	0.943	0.991	0.994	0.991	0.994
AIC	-697.009	-747.141	-1953.078	-2155.617	-1930.454	-2154.381
BIC	-594.216	-724.795	-1926.272	-2052.860	-1912.583	-2047.156

Note: The numbers in brackets are standard errors. ＊ $p < 0.10$, ＊＊ $p < 0.05$, ＊＊＊ $p < 0.01$.

$$\ln(ED_{it}) = -0.722 + 0.210 \times \ln(\mathrm{GDP}) - 0.009 \times \ln(GDP)^2 + 0.941 \times \ln\left(ED_{i,t-1}\right)$$

To forecast the electricity demand of each province in 2030, it is necessary to forecast the values of GDP per capita of each province. Lin (2021) predicts that China's economy can achieve an average annual growth rate of 6% from 2020 to 2035[21]. We assume that the per capita GDP growth rate of each province will remain consistent (6%) in the next decade.

A.2 Input-output price model

Table A2 shows a schematic non-competitive input-output table for a typical open national economy, including n domestic industrial sectors (denoted as sectors 1 to sector n) and m foreign sectors (denoted as sector n+1 to n+m).

Table A2
Schematic non-competitive input–output table for a typical open national economy

		Intermediate use				Final demand		Total output
		Sector 1	Sector 2	…	Sector n	Domestic use	Foreign use	
Domestic input	Sector 1							
	Sector 2							
	…							
	Sector n							
Foreign input	Sector n+1							
	Sector n+2							
	…							
	Sector n+m							
Value-added	Wages							
	Taxes							
	Depreciation							
	Surplus							
Total input								

Suppose the price of the last domestic sector n (the production and supply of electricity and heat sector) increases by Δp_n . Under the condition that the production technology remains unchanged, the cost of the unit output value of endogenous sectors (sector 1 to sector n-1) will increase by $\Delta p_n * a'_{1,n-1}$, where $a'_{1,n-1}$ is the column vector obtained by removing a_{nn} in the nth row of the direct consumption coefficient matrix, which is represented by A. The direct consumption coefficient $a_{i,j}$ refers to the value of the goods or services produced by sector i and directly consumed by the unit total output of sector j, as shown in Eq.(A1). So, the prices of these endogenous sectors will increase by $\Delta p_n * a'_{1,n-1}$, which leads to a continuing increase ($\Delta p_n * A'_{1,n-1} * a'_{1,n-1}$) in the costs and prices of these endogenous sectors, where $A'_{1,n-1}$ is a transposition of the direct consumption coefficient matrix excluding row n and column n. By analogy, the increase in the cumulative prices in the endogenous sectors can be calculated by Eq.(A2).

$$a_{i,j} = \frac{x_{i,j}}{x_j} \qquad (A1)$$

$$\Delta p_{1,n-1} = \left(I_{n-1} - A'_{1,n-1}\right)^{-1} * a'_n * \Delta p_n \qquad (A2)$$

where $x_{i,j}$ stands for the value of the products or services produced by sector i and consumed by sector j. x_j stands for the total output in sector j. $A_{1,n-1} = \begin{bmatrix} a_{1,1} & \cdots & a_{1,n-1} \\ \vdots & \vdots & \vdots \\ a_{n-1,1} & \cdots & a_{n-1,n-1} \end{bmatrix}$. $\Delta p_{1,n-1}$ stands for the column vector indicating the price increase from sector 1 to sector n-1. I_{n-1} is a unit matrix of order n-1.

So far, this paper has obtained the price changes of all domestic sectors by Eq.(A2). Then the changes of CPI, PPI, and GDP can be calculated using the corresponding weights.

$$\text{CPI changes} = \frac{\Delta p_{1,n}{}' \begin{bmatrix} C_1 \\ \vdots \\ C_n \end{bmatrix}}{\sum_{i=1}^{n} C_1} \qquad (A3)$$

$$\text{PPI changes} = \frac{\Delta p_{s,t}{}' \begin{bmatrix} P_s Q_s \\ \vdots \\ P_t Q_t \end{bmatrix}}{\sum_{i=s}^{t} P_i Q_i} \qquad (A4)$$

$$\text{GDP deflator changes} = \frac{\Delta p_{1,n}{}' \begin{bmatrix} V_1 \\ \vdots \\ V_n \end{bmatrix}}{\sum_{i=1}^{n} V_i} \qquad (A5)$$

where C_i stands for the consumption in sector i. $P_t Q_t$ stands for the total output in industrial sector t, and sector s and sector t are the first and the last domestic industrial sector, respectively. V_i stands for the value-added in sector i.

A.3 Model parameter setting

A.3.1 Transmission cost

The Northeast and Northwest regions, with flat and open terrain, are rich in wind and solar energy resources. They are the main gathering places of wind and solar plants and also the most serious areas of wind curtailment and solar curtailment in recent years. On the contrary, China's power load centers are mainly concentrated in the North, Eastern Coastal, and Southern regions. Under the mandatory quota of renewable power consumption, the East, Central, North, and South regions need to consume more renewable energy. To balance the development of renewable power centers and load centers, it is necessary to carry out long-distance electricity transmission. Combined with the actual situation, the Northeast and Northwest are set as the output places of renewable power, and the East, Central, North, and South regions are set as the input places of renewable electricity.

The transmission cost is closely related to the transmission distance. We firstly estimate the distance between the electricity output regions and other regions. Combined with the load situation, wind and solar energy resources, geographical location, etc., the distance between regions is replaced by the distance between the central cities in each region (see Table A3).

Table A3
Distance between regions (unit: km)

	Central (Wuhan)	East (Hangzhou)	South (Guangzhou)	North (Beijing)
Northeast (Changchun)	2137	2173	3133	979
Northwest (Xining)	1679	2239	2627	1819

Source: http://www.gditu.net/

The transmission cost between regions is equal to the sum of the regional grid energy price, inter-regional grid transmission price, and line loss price. The regional grid energy price is based on *the notice on the approval of transmission price of regional grid from 2020 to 2022* issued by NDRC.[3] We assume the transmission price and line loss price are proportional to the transmission distance. In determining the transmission price and line loss rate of unit distance, we calculated the average transmission price and line loss rate of 16 Ultra High Voltage (UHV) transmission lines in China, as shown in

Table A4
Transmission price per unit distance and line loss price

Transmission Line	Distance (km)	Transmission price (yuan/thousand kWh)	Transmission Price per unit distance (yuan/ thousand kWh/km)	Line loss rate	Line loss price (yuan/thousand kWh)[1]	Line loss price per unit distance (yuan/thousand kWh)
Longzheng	860.4	67.5	0.078	7.5%	30.042	0.035
Genan	1110.1	55.8	0.050	7.5%	30.042	0.027
Linfeng	978.0	43.9	0.045	7.5%	30.042	0.031
Yihua	1048.5	68.5	0.065	7.5%	30.042	0.029
Jiangcheng	940.7	38.5	0.041	7.7%	30.693	0.033
Huliao	913.0	42.0	0.046	4.1%	15.921	0.017
Qingzang	2530.0	60.0	0.024	13.7%	58.820	0.023
Jinsu	2057.9	51.1	0.025	7.0%	27.889	0.014
Xiangshang	1907.0	57.1	0.030	7.0%	27.889	0.015
Binjin	1705.0	45.4	0.027	6.5%	25.758	0.015
Debao	534.3	33.6	0.063	3.0%	11.459	0.021
Jinnanjing	654.0	25.1	0.038	1.5%	5.642	0.009
Hazheng	2210.0	61.3	0.028	7.2%	28.747	0.013
Ningdong	1333.0	50.8	0.038	7.0%	27.889	0.021
Jiuhu	2383.0	60.2	0.025	6.5%	25.758	0.011
Xiguang	1224.7	49.5	0.040	6.5%	25.758	0.021
Average			0.041			0.021

Source: NDRC. https://www.ndrc.gov.cn/?code=&state=123:

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[3] Source: https://www.sohu.com/a/425405009_749304

Table A4. To determine the line loss price of unit distance, besides the average line loss rate, the on-grid price needs to be determined. Because wind generation and solar generation will enter the parity era in the next ten years, the cost of renewable energy generation will be similar to the cost of thermal power. Therefore, the forecast renewable energy on-grid price in 2030 is replaced by the average on-grid price of thermal power in 2019.

We do not consider the new long-distance transmission lines, assuming that there is no capacity limit for the transmission line between regions. Based on the above analysis, the transmission cost calculated is shown in Table A5.

Table A5

Average electricity price increase in regions (unit: cent)

Region	Average electricity price increase
North	5.9
East	4.8
Central	6.0
Northeast	5.9
Northwest	4.7
South	4.3
Nationwide	**5.4**

A.3.2 Wind and solar capacity construction cost

The new installation cost includes the equipment cost, construction and installation cost, and operation and maintenance cost, among which the equipment cost accounts for more than 50% of the total new installation cost. In the past decade, because of the maturity of related technologies, the equipment cost of wind and solar has decreased rapidly in the world. According to the relevant information of the National Energy Administration (NEA), from 2007 to 2017, the cost of solar generation has decreased by about 90% and the cost of onshore wind generation has decreased by more than 40%.[4] In the future, the equipment cost of wind and solar will drop. According to the prediction data of Energy Intelligence, by 2030, the new installation cost of wind power will be 15% lower than that of 2020, and the installation cost of solar will be 25% lower than that of 2020.[5] We assume that the price of renewable energy equipment is the same in each province, and ignores the transportation cost from the production to the installation site, that is, the new installation costs in the six regions are the same. It is calculated that the average installed cost of wind in the next ten years is 7.15 million yuan/MW, and the average installed cost of solar is 3.99 million yuan/MW.

A.3.3 Power generating hours

The generating hours of wind and solar can reflect the local wind and solar resources to a certain extent and change little with time. We assume that the generating hours in 2030 are the same as in 2019. According to the generating hours and installed capacity of each province in each region, the average generating hours of wind and solar can be calculated, as shown in Table A6.

Table A6

Generating hours of wind power and solar PV

Region	Generating hours of wind	Generating hours of solar
North	1986.66	1239.82
East	2092.90	1029.64
Central	1887.58	1004.02
Northeast	2296.46	1536.67
Northwest	1933.82	1358.16
South	2270.37	1111.30

A.4 Provincial deployment index and results under 2 indicators

(1) Integration capacity index

Grid-integration is a problem that limits the development of renewable energy. To promote the nearby integration of renewable energy and reduce the electricity transmission cost, more installed capacity should be deployed in areas with strong integration capacity. The influencing factors include electricity generation, electricity grid, electricity user, and the market mechanism. In consideration of the availability of data, we define the integration capacity index from the power generation. Due to the instability of renewable power, thermal power and hydropower are required to provide corresponding peak load regulation capacity and reserve capacity. Provinces with more thermal power and hydropower can provide more auxiliary capacity to coordinate local integration of renewable electricity, stabilize the electricity supply, and meet the continuous electricity demand. The allocation index based on the provincial integration capacity is as follows:

$$Q_{ij} = Q_i * \frac{AI_{ij}}{\sum_j^{M_i} AI_{ij}} \qquad (A6)$$

where Q is the renewable energy installed capacity, AI_{ij} is the installed capacity of hydropower and thermal power, i is the region, j is the province in the region, and M is the number of provinces in the region.

(2) Environmental pressure index

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[4] Source: http://www.nea.gov.cn/

[5] Source: http://guangfu.bjx.com.cn/news/20200615/1080960.shtml

The provinces with greater environmental pressure generally have greater responsibility for emission reduction. Renewable energy could help curb local emissions of greenhouse gases and pollutants. As the major sector of energy consumption and emission, industrial emissions account for about 70% of the total greenhouse gas emissions in China. In this study, the industrial electricity consumption proportion in 2019 is used as an alternative index of environmental pressure in different provinces. The allocation index based on environmental pressure is as follows:

$$Q_{ij} = Q_i * \frac{IE_{ij}}{\sum_j^{M_i} IE_{ij}} \qquad (A7)$$

where Q is the renewable energy installed capacity, IE_{ij} is the industrial electricity consumption, i is the region, j is the province in the region, and M is the number of provinces in the region.

The consumption capacity index is measured by the proportion of the alternative power capacity between different provinces in the region, and the environmental pressure index is replaced by the proportion of the industrial power in the region. The consumption capacity represents the upper limit of the clean power consumption capacity in the region, while the environmental pressure index focuses on the regional emission reduction responsibility. In the actual regional planning of renewable power, these two dimensions usually need to be considered comprehensively. In addition, many factors affect renewable energy planning at the provincial level. In addition to the above two factors, local finance, local terrain, wind speed, and so on will restrict the power plant construction. However, in the overall planning, the capacity of consumption and the responsibility of regional emission reduction are the most important factors for local renewable energy planning. This study presents the provincial allocation scheme of new energy installation from these two dimensions, which can reflect the future renewable energy capacity situation of each province to a certain extent and provide a reference for the national renewable power development. Table A7 shows the provincial allocation results of the new installed capacity based on different indicators.

Table A7

Provincial allocation results of the new installed capacity based on different indicators (unit: GW)

Region	Province	Allocation by consumption capacity index	Allocation by environmental pressure index
North	Beijing	8.6	5.8
	Tianjin	11.4	10.2
	Hebei	36.2	46.6
	Shanxi	47.9	31.3
	Shandong	74.6	84.7
East	Anhui	28.6	19.2
	Shanghai	12.3	9.8
	Jiangsu	51.8	57.7
	Zhejiang	35.8	42.6
	Fujian	20.4	19.7
Central	Jiangxi	13.1	19.5
	Henan	36.7	43.1
	Hubei	33.5	26.9
	Hunan	17.7	19.7
	Chongqing	10.9	14.0
	Sichuan	44.8	33.5
Northeast	Liaoning	50.4	66.2
	Jilin	30.9	18.1
	Heilongjiang	31.8	23.0
	Inner Mongolia	117.3	123.1
Northwest	Shaanxi	49.9	43.0
	Gansu	33.9	32.4
	Qinghai	18.5	21.2
	Ningxia	35.8	32.5
	Xinjiang	69.1	79.1
	Tibet	2.4	1.3
South	Guangdong	42.0	59.5
	Guangxi	16.5	18.2
	Hainan	2.6	2.1
	Guizhou	23.1	14.7
	Yunnan	29.0	18.9