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Scenarios Analysis on the Regional Pathway under the Target of Carbon Peak and Carbon Neutrality： a Case Study of Sichuan Province

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ABSTRACT

This study proposed a regional low-carbon development pathway evaluation model under the carbon peak and carbon neutrality (CPCN) targets. First, regional economic and social development goals, carbon reduction targets and scenarios is set in a top-down manner. Secondly, it designs the development scenarios and goals for different sectors including industry, building, transportation and energy supply. Then, it carries out the integration, evaluation and iteration of these bottom-up solutions until consistent with the set goals. Finally, an empirical study of Sichuan Province using the model is conducted. The results show that (1) under the CPCN scenario, Sichuan's carbon emissions will peak at 253.1 million tons in 2028 and drop to 44.8 million tons in 2057, and carbon neutrality of energy consumption can be achieved there; (2) carbon peak will be achieved in different sectors in the order of industry (2022), transportation (2030) and construction (2035) and among all energy varieties in the sequence of coal (2015), oil (2025) and gas (2040) in a coordinated, stepwise and well-organized manner; (4) under the carbon neutrality target, Sichuan's electrification level will rise from 34.7% in 2015 to 75.0% in 2057, and the share of non-fossil power on the supply side will rise from 86.1% in 2015 to 95.7% in 2057.

Keywords: Carbon Peak; Carbon Neutrality; Scenario Analysis; Regional pathway; Sichuan Province

NONMENCLATURE

Abbreviations	
AD	Activity Level
BAU	Business As Usual
C	Consumption
CE	Carbon Emission
CPCN	Carbon Peak and Carbon Neutrality
EF	Carbon Emission Factor
EI	Energy Intensity
GDP	Gross Domestic Product
GC	Power Generation Capacity
NDCs	Nationally Determined Contributions
RE	Carbon Emission Reductions
RLCDPEM	Regional Low-carbon Development Pathway Estimation Model
S	Supply
Symbols	
ρ	proportion
Subscripts	
i	energy consumption sectors
j	types of energy
t	years
Superscripts	
el	electricity
exp	export of electricity
he	heat
imp	import of electricity
pow	local thermal power

1. INTRODUCTION

At the Paris Climate Conference 2015, a global consensus was reached on holding the increase in the global average temperature to well below 2 °C above the pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels[1]. According to the current emission trends and the current efforts countries in the world, the global average temperature increase will reach 3-4 °C, bringing the sea level up by 0.6-0.8m and causing irreversible ecological catastrophes and economic losses worldwide[2]. Moreover, according to the assessment of the Intergovernmental Panel on Climate Change (IPCC), achieving the 2 °C and 1.5 °C target would require the world reach carbon neutral by 2070 and by 2050[3]. Against this backdrop, Chinese President Xi Jinping announced that China will have CO_2 emissions peak before 2030 and achieve carbon neutrality before 2060[4], and further stressed that the Party committees and governments at all levels should develop clear timelines, roadmaps and work plans. In response to this, all Chinese provinces and municipalities are conducting research on the development pathway under the CPCN targets.

At present, many developed countries have peaked their CO_2 emissions and are committed to carbon neutrality research and practice. They peaked their CO_2 emissions naturally in accordance with the law of economic and social development, which is different from the case in China, which sets the time to peak its CO_2 emissions to push the reform and transformation of energy systems and technologies. Therefore, this paper sets up a regional low-carbon development pathway estimation model (RLCDPEM) combining top-down and bottom-up approaches. The model considers social and economic development goals and the CPCN targets from top to bottom; designs from bottom up the development scenarios and goals for industry, building, transportation and energy supply sectors respectively from the perspective of controlling the demand for energy services, improving energy efficiency, optimizing the energy mix and making electricity cleaner; and finally carries out the integration, evaluation and iteration of these bottom-up solutions, until a systematic one consistent with the top-down goals is found.

This paper consists of the following: Sections 2.1 and 2.2 systematically introduce the regional low-carbon development pathway estimation model and the calculation methods. Section 2.3 describes the input data and scenarios setting through a case study of Sichuan Province. Section 3 demonstrates and analyzes the development path of Sichuan Province . The key points of the development path of Sichuan Province in section 4.

2. METHODOLOGY

2.1 *Modelling framework*

RLCDPEM under the CPCN targets established in this paper, as shown in Fig. 1, conducts scenario analysis of different sectors in aspect of controlling energy services, improving energy efficiency, optimizing the energy mix and power supply structure in line with provincial (municipal) macro socioeconomic development indicators such as GDP, population and urbanization, and in the light of the historical variation trends of energy consumption sectors. By doing so, the model obtains energy of different categories consumed in each sector and then, according to the carbon emission factors of different categories of energy, figures out the carbon emissions in each sector.

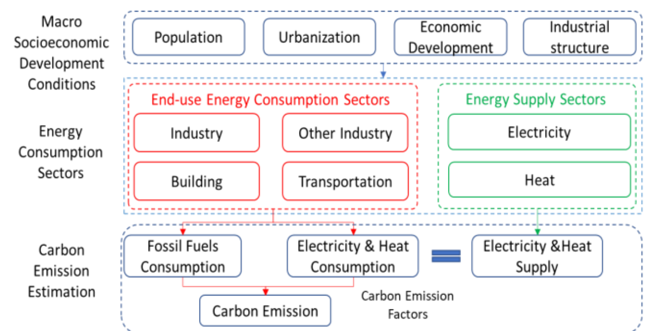

Fig 1 Framework of RLCDPEM.

It should be noted that the estimation boundary assumed by the model laid down in the *Guidelines for the Development of Provincial Action Plans for Peaking Carbon Dioxide Emissions* issued by the Ministry of Ecology and Environment[5], which only applies to carbon emissions from energy consumption of these sectors. Specifically, these involve end-use energy consumption sectors (a) industry, including energy-intensive industries (e.g., steel, non-ferrous, petrochemical, chemical, building materials, etc.) and other industrial sectors; (b) building, including urban and rural residential building, and public building; (c) transportation, including commercial (excluding civil aviation) and non-commercial transportation; (d) other industry sectors, including agriculture, construction industry; and (e) energy supply, including electricity and heat supply. The electricity and heat consumption in industry, building, transportation and other industry sectors should be in balance with the electricity and heat supply in the energy supply sector.

2.2 Mathematical formulation

On the grounds of the boundary shown in Fig.1, we have established a carbon emission estimation module for each sector.

2.2.1 Carbon emission estimation module for end-use energy consumption sectors

Carbon emissions from end-use energy consumption sectors are calculated through Formula (1)

$$CE_{i,t} = \sum_{j} AD_{i,t} \times EI_{i,t} \times \rho_{i,j,t} \times EF_j \quad (1)$$

Where, $CE_{i,t}$ represents carbon emissions from sector i in year t, $AD_{i,t}$ is the activity level of sector i in year t, $EI_{i,t}$ is the energy intensity per unit of activity level of sector i in year t, $\rho_{i,j,t}$ is the proportion of category j energy in the energy mix of sector i in year t, and EF_j is the carbon emission factor of category j energy.

It should be noted that the meaning of the activity level ($AD_{i,t}$) varies from sector to sector. For industry and other industrial sectors, the activity level of each sector is the added value of the sector (10^4 CNY). For the building sector, the activity level means the floor space (m^2). For the transportation sector, the activity level refers to the traffic turnover (passenger or ton kilometer) or the vehicle kilometers traveled (km).

Energy of different categories is standardized, with electricity so treated with the power generation coal consumption method[6]. The carbon emission factors assumed in this study are as follows: Coal, oil, and gas are 2.66 tCO_2/tce, 1.73 tCO_2/tce, and 1.56 tCO_2/tce respectively; other non-fossil fuels (e.g., straw, biogas, firewood, etc.) refer to 0[5]; for carbon emission factors of electricity and heat, please see Formulas (9) and (10) in section 2.2.2.

2.2.2 Carbon emission estimation module for the energy supply sector

In this module, the supply of electricity and heat should be in balance with the consumption in each end-use energy consumption sector as mentioned in section 2.2.1, which means that Formulas (2) and (3) should be satisfied.

$$S_t^{el} = C_t^{el} = \sum_{i} AD_{i,t} \times EI_{i,t} \times C_{i,t}^{el} \quad (2)$$

$$S_t^{he} = C_t^{he} = \sum_{i} AD_{i,t} \times EI_{i,t} \times C_{i,t}^{he} \quad (3)$$

Where, S_t^{el} and C_t^{el} stand for the electricity supply and consumption respectively in year t, S_t^{he} and C_t^{he} are the heat supply and consumption in year t, and $C_{i,t}^{el}$ and $C_{i,t}^{he}$ represent the electricity and heat consumed by end-use sector i in year t.

1) Carbon emissions from electricity are calculated using Formula (4).

$$CE_t^{el} = CE_t^{pow} + CE_t^{imp} \; or$$
$$= CE_t^{pow} - CE_t^{exp} \quad (4)$$

Where, CE_t^{el} means the carbon emissions from electricity in year t, CE_t^{pow} is the carbon emissions from local thermal power in year t, and CE_t^{inp} and CE_t^{exp} are the carbon emissions from electricity transferred to and from a region respectively in year t.

In this case, CE_t^{pow} is calculated according to Formula (5).

$$CE_t^{pow} = \sum_{j} GC_{j,t} \times EC_{j,t} \times EF_j \quad (5)$$

Where, $GC_{j,t}$ is the amount of electricity generated from category j fossil energy in year t (e.g., coal power and gas power), and $EC_{j,t}$ means the average power generation efficiency of category j fossil energy in year t.

For a region from which electricity is transferred, carbon emissions from the net electricity transferred (CE_t^{imp}) is calculated through Formula (6).

$$CE_t^{imp} = EQ_t^{imp} \times EF_t^{imp} \quad (6)$$

Where, EQ_t^{inp} is the net amount of electricity transferred to a region in year t, while EF_t^{inp} is the carbon emission factor of electricity in the export region in year t.

For a region to which electricity is transferred, the most critical assumption of our work is that the receiving region should assume some of the responsibility for carbon emissions from local thermal power plants, so such carbon emissions will be calculated via Formula (7).

$$CE_t^{exp} = CE_t^{pow} \times (EQ_{,t}^{exp} / (S_t^{el} + EQ_{,t}^{exp})) \quad (7)$$

Where, $EQ_{,t}^{exp}$ means the net amount of electricity transferred from a region in year t.

2) Carbon emissions from heat are calculated through Formula (8).

$$CE_t^{he} = \sum_{j} S_t^{he} \times \rho_{j,t}^{he} \times EC_t^{he} \times EF_j^{he} \quad (8)$$

Where, CE_t^{he} is the carbon emissions from heat in year t, $\rho_{j,t}$ is the proportion of category j energy in the heating energy mix in year t, and EC_t^{he} is the average heating efficiency in year t.

3) Carbon emission factors from electricity and heat in a region are calculated under Formulas (9) and (10) respectively.

$$EF_t^{el} = CE_t^{el} / C_t^{el} \quad (9)$$

$$EF_t^{he} = CE_t^{he} / C_t^{he} \quad (10)$$

2.3 A case study of Sichuan Province

2.3.1 Data input

Based on the historical data on Sichuan Province during 2015-2020[7][8], this study inputs four types of data, namely population, urbanization, economic development and industrial structure, into RLCDPEM.

1) Population: the annual average growth rate of permanent population in Sichuan was 0.4% during 2015-2020, so the annual average growth rate of permanent population during 2021-2060 is set at 0.4%, and the permanent population is expected to reach 86.7 million and 96.2 million in 2030 and 2060 respectively.
2) Urbanization: the urbanization rate of permanent population in Sichuan Province in 2020 was 56.7%, up 9.0% from 2015, still below the Chinese average (63.9%). As Sichuan Province will come to the stage of rapid urbanization and finally develop into a developed region (e.g., Beijing, Shanghai, where the urbanization rate exceeds 80%) in China, the urbanization rate in Sichuan Province is set to reach 68% and 80% respectively in 2030 and 2060.
3) Economic development: the annual average GDP growth rate in Sichuan was 7.8% during 2015-2019, above the national average (6.7%) during that period, but its per capita GDP (CNY 55,661 in 2019) was still below the national average (CNY 70,774 in 2019). Looking into the future, we believe that Sichuan Province will further speed up economic development with the construction of the "Chengdu-Chongqing Economic Circle" to overtake the national level. Hence, the economic growth rate of Sichuan is set to exceed the national average[9], so that the per capita GDP will reach CNY 107,000 and CNY 344,000 respectively in 2030 and 2060.
4) Industrial structure: during 2015-2020, Sichuan Province witnessed a shift in the industrial structure from 12.2:44.1:43.7 to 11.4:36.2:52.4. Looking ahead, Sichuan will continue to promote the development of the tertiary industry, and the industrial structure is expected to be 7.5:32.0:60.5 and 3.0:27.0:70.0 in 2030 and 2060 respectively.

2.3.2 Scenarios setting

While meeting the socioeconomic development conditions as envisaged in section 2.3.1, this study takes into account two scenarios: one is the BAU scenario, the other is the CPCN scenario aiming at achieving the carbon peak and carbon neutrality targets. Compared with the BAU scenario, the CPCN scenario optimizes the industry, building, transportation and energy supply sectors in Sichuan Province by reasonably controlling the demand for energy services, improving energy efficiency, promoting energy alternatives, and developing clean power.

3. RESULTS AND DISCUSSION

Using the model described in 2.2 and the data input and scenarios setting in 2.3, this study demonstrates the carbon emission pathways under the BAU and CPCN scenarios in Sichuan Province on the premise of meeting the socioeconomic development goals there. The results, as shown in Fig.2, suggest that carbon emissions will peak in 2034 and 2028 respectively under the two scenarios, at 277.5 million tons and 253.1 million tons. In 2060, carbon emissions will reach 149.0 million tons and 12.9 million tons under the BAU and CPCN scenarios respectively, down 37% and 94% from the 2015 levels. Given the abundant carbon sink resources in Sichuan Province (47.8 million tons in 2018), carbon emissions will drop to 44.8 million tons in 2057 under the CPCN scenario, and carbon neutrality of energy consumption can be achieved. Next, we will further analyze the pathway of Sichuan Province under the CPCN scenario.

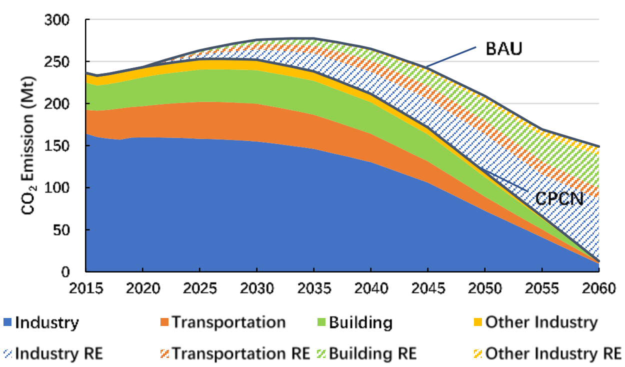

Fig 2 The pathway of Sichuan Province under the CPCN scenario.

3.1 Analysis of the carbon peak pathway

Under the CPCN scenario, differences are observed in terms of energy category and variation trend of carbon emissions in each end-use energy consumption sector. From the perspective of end-use energy consumption (as shown in Fig.3), carbon emissions from coal, oil and gas will peak in 2015, 2025 and 2040 respectively, at 129.4 million tons, 61.5 million tons and 74.2 million tons. In 2029, carbon emissions from coal will be 2.5 million tons less than the 2028 level, those from oil 0.2 million tons less and those from gas 2.2 million tons more, indicating that even though the time when carbon emissions from gas peak is later than that of carbon peak (in 2028) in

Sichuan Province, the decrease in carbon emissions from coal and oil will have been greater than the increase in carbon emissions from gas by that time, thus achieving the overall peaking of carbon emissions in 2028.

In end-use energy consumption sectors (as shown in Fig.4), carbon emissions from industry, transportation and building will peak in 2022, 2030 and 2035 respectively, at 159.7 million tons, 44.8 million tons and 40.2 million tons. In 2029, carbon emissions from industry will be 0.80 million tons less than the 2028 level, those from transportation 0.12 million tons more and those from building 0.34 million tons more, implying that even though the transportation and building sectors fail to have their carbon emissions peak in 2028, the decrease in carbon emissions from industry will have been greater than the increase in carbon emissions from transportation and construction by that time, thus achieving the peaking of carbon emissions in Sichuan Province in 2028.

3.2 Analysis of the carbon neutrality pathway

In 2057, the total carbon emissions from Sichuan Province will decrease from 161.1 million tons under the BAU scenario to 44.8 million tons; to break it down, emission reductions in industry, transportation and building will be 59.2 million tons, 14.7 million tons and 33.8 million tons relative to the BAU scenario (as shown in Fig.5).

The largest share of such emission reductions will come from industry, standing at 50.9%, of which 5.7% will be owed to optimizing the industrial structure, 6.5% to improving energy efficiency and 87.8% to optimizing the energy mix, including zero-carbon power. Below are the reasons why optimizing the energy mix will make the largest contribution. On the one hand, this will be achieved by increasing the level of electrification industrial end-use energy consumption and the share of non-fossil power on the supply side: end-use power consumption in industry will climb from 29.2% in 2015 to 70.7% in 2057 and the share of non-fossil power on the supply side will rise from 86.1% in 2015 to 95.7% in 2057. On the other hand, hydrogen energy and biomass will be introduced in 2030 to iron & steel, chemical, petrochemical and other industries as zero-carbon energy resources or raw materials, which will account for 9.8% in 2057.

In the building sector, controlling the per capita floor space within 60 m^2, relative to 65 m^2 under the BAU scenario, can give rise to a 7.7% reduction in carbon emissions. Reducing energy consumption per unit area will help reduce carbon emissions by 8.6% and

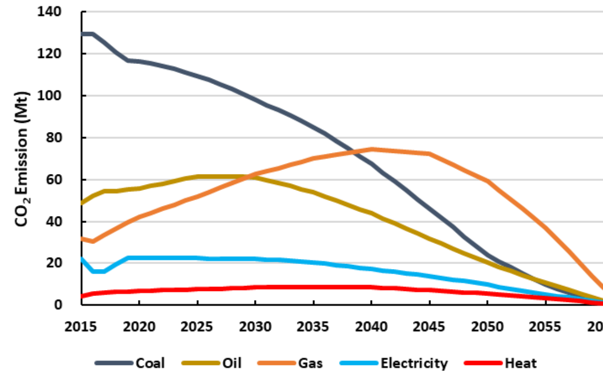

Fig 3 Ccarbon emissions from end-use energy in Sichuan under the CPCN scenario.

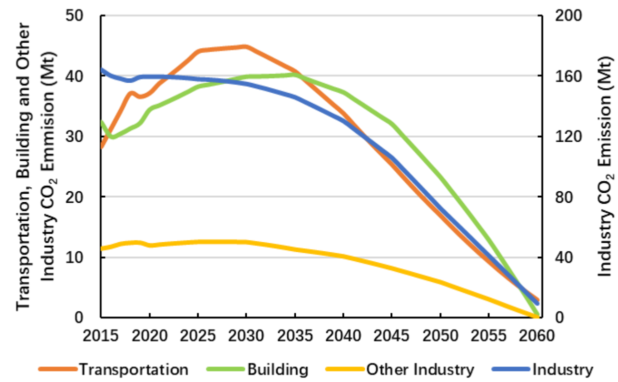

Fig 4 Carbon emissions from end-use energy consumption sectors in Sichuan under the CPCN scenario.

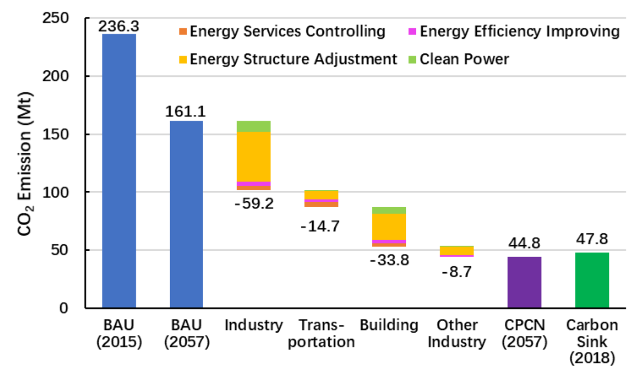

Fig 5 Implementation steps of Sichuan Province to meet its carbon neutralty target.

optimizing the energy mix and zero-carbon power will contribute 83.7% to carbon emission reduction.

In the transportation sector, controlling the ownership of private cars in every 1,000 people at 280, relative to 310 under the BAU scenario, will result in a 26.6% reduction in carbon emissions. Raising the electrification level of private cars to 82% from the BAU level of 59% will have carbon emissions reduced by 56.2%.

4. CONCLUSION

In order to provide different regions with carbon emission reduction pathways under the CPCN targets, this study establishes a regional low-carbon development pathway estimation model. The model can set future development goals for industry, building, transportation and energy supply sectors in terms of controlling the demand for energy services, improving energy efficiency, optimizing the energy mix and developing clean power, taking into account the set targets for regional economic and social development and people's living standards, as well as the constraints from the CPCN targets, and deduce pathways that satisfy the goals and targets.

Using the model and based on the historical data on Sichuan Province during 2015-2019, this study provides its pathway under the given provincial socioeconomic development goals and CPCN targets. On the grounds of this pathway, the study gives the development pathways of coal, oil, gas and power, and the pathways for industry, building and transportation to peak carbon emissions, under the target of peaking carbon emissions from energy consumption in 2028 and achieving carbon neutrality in 2057 in Sichuan Province. The results suggest that Sichuan Province should achieve its CPCN targets by improving the flexibility of its power systems and the level of electrification of end-use energy consumption in a coordinated manner and then promoting the peaking of carbon emissions from coal, oil and gas in succession in industry, transportation and building one after another in the principle of "stepwise, well-organized and coordinated peaking of carbon emissions". In addition, advancing the electrification of end-use energy consumption and the development of zero-carbon power is the most effective measure for Sichuan Province to achieve its CPCN targets. In the year when carbon emissions will peak (2028), the electrification level of end-use energy consumption and the share of non-fossil power will reach 43.7% and 90.1% respectively. In the year when carbon neutrality will be achieved (2057), the two indicators will reach 75.0% and 95.7% respectively.

However, the model established in this study still has some limitations that need to be solved in the future. In the first place, the carbon emission estimation boundary of this model only applies to carbon emissions from energy consumption, but not those from non-energy activities and non-CO_2 gases, relative to the boundary of greenhouse gas inventories; secondly, the model takes into account only the balance between power and heat supply and demand under the CPCN targets, but lacks reasonable considerations on the supply of fossil energy and the development sequence and layout of renewable energy; thirdly, the model does not consider economic optimization in setting the development goals and implementation pathways for industry, construction, transportation and energy.

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