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Coal power demand and paths to peak carbon emissions in China: A provincial scenario analysis oriented by CO_2-related health impact

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Abstract—The pace of emissions reduction in coal power strongly affects the peaking time of total CO_2 emissions in China. Applying Kaya identity, Rollback model, and health impact assessment model, this study proposes an integrated framework for simulating coal power demand and the related CO_2 emissions in China's 29 provinces during 2020-2035, with the evaluation of CO_2-related health impact in life and economic loss. It is found that the total coal power demand in China kept rising by 5.19% per year in 2009-2019. And the projection demand would still increase, ranging from 4687.26 to 8897.13 billion kW·h under the BAS scenario. Results of spatial heterogeneity show that East China would contribute to the greatest CO_2 emissions, valuing as 149.47, 156.11, and 190.21 mg/m^3 of CO_2 concentrations for the period of 2020-2025, 2026-2030, and 2031-2035. Rapid development scenario (RDS) suggests a potential emission reduction path, in which could avoid life loss of 10539 years and economic loss of 1.07 billion dollars nationwide during 2020-2035. Our findings could provide a deeper understanding of potential peaking paths by provinces, and also assist policymakers in better establishing emissions reduction targets for other nations from a top-down perspective, thus could be of global significance.

Keywords—coal power demand; carbon peaking; health impact; CO_2 emissions

I. INTRODUCTION

Climate change is one of the most complicated global issues confronting humankind in the 21st century [1]. To combat global warming, the Paris Agreement has committed to limit the increase in global temperature to 1.5℃ or well below 2℃. To this end, over 100 national governments and more than 800 cities have pledged or are considering net-zero emissions targets [2]. However, it is assessed that the global emissions continue reaching a record-high level of 40.8 Gt in 2021 [3]. The risk and challenge induced by climate change are still enormous. Under such severe circumstances, as the largest emerging economy worldwide whose CO_2 emissions accounted for approximately 30.9% of the global emissions in 2020 [4], China has officially declared to ensuring that its CO_2 emission peak by 2030 and attaining carbon neutrality before 2060.

Realizing carbon peaking and carbon neutrality targets in China calls for a rapid and profound energy decarbonization, and progress in three key areas assumes considerable importance, namely, advances in energy efficiency, developing renewable energy, and reducing coal utilization [5]. And as the largest coal-fired power plant fleet, China's power sector contributed to nearly 5.4 billion tons of CO_2 emissions, taking up about 47% of the total emissions in the national energy systems. It should be noted that even though the COVID-19 pandemic is still ongoing, the emissions of power sector increased by 2% in 2020 [4]. Herein, large electricity demand and coal-dominant structure of power generation are the main drivers for the carbon emissions increment. It is estimated that coal power decline is limited and would continue to be main electricity supplier, even though non-fossil energy accounts for nearly 25% of primary energy consumption by 2030 in China [6].

Given the importance of China's coal power sector in the realization of the national peak target, it is essential to quantitatively clarify the coal power demand and the CO_2 emission peaking paths in the next few years. Nowadays, many scholars have devoted themselves to forecast the revolution of power system and the changes of power demand, which could be generally divided into two major pathways, namely, *top-down* and *bottom-up* prediction models. The former approaches explore the low-carbon development of the power sector from a macroeconomic perspective [7][8]. Specifically, the development of economy and society is regarded as an interactive system, various factors such as GDP, population size, and urbanization rate are included. Comparatively, complex energy sectors in different regions can be investigated from a technical perspective using the *bottom-up* models. In more detail, the main characteristics, complex internal relationships, and external constraints of energy system are described, to further analyze how policy instruments affect technologies [9][10]. Further, as one of the important motivations for climate change mitigation actions, health-related air quality co-benefits have attained widespread attention from scholars and policy-makers when discussing carbon peaking and carbon neutrality targets [11]. Regarding this, many studies conduct the assessments via multi-model coupling of "Energy economy scenario - Air quality simulation - Health impact assessment - Health impact monetization", to evaluate the health co-benefits of air quality improvement under different scenarios, and propose the countermeasures which could synergistically address issues of climate change and human health [12].

However, to the best of our knowledge, little consideration is given to the single coal power sector in the existing literature, and future emissions induced by coal power demand between various provincial regions in China have not been analyzed comparatively. Moreover, the evaluation indicators mainly concentrate on $PM_{2.5}$ emissions, which have not yet extended to CO_2 emissions-related health impact. Actually, the provincial level is the actual executor to implement the emission reduction policy, and there are vast differences of energy endowment and development level among Chinese regions. It is of vital importance to explore the potential spatial heterogeneity of coal power demand and the related carbon emission. Therefore, combing with static scenario setting and dynamic scenario simulation, the objective of this study is to develop an analytical framework for simulating China's coal power demand and CO_2 emissions at the provincial level, with the viewpoint of CO_2-related health impact. And a set of strategies for low carbon transition in Chinese coal power sector are suggested, which would help to provide theoretical references and decision basis for promoting the sustainable development of coal power industry.

II. Model Development

An integrated analytical model is proposed in this study, as shown in Fig. 1, three modules are included to establish systematic linkages between energy demand, carbon emissions, and health impact.

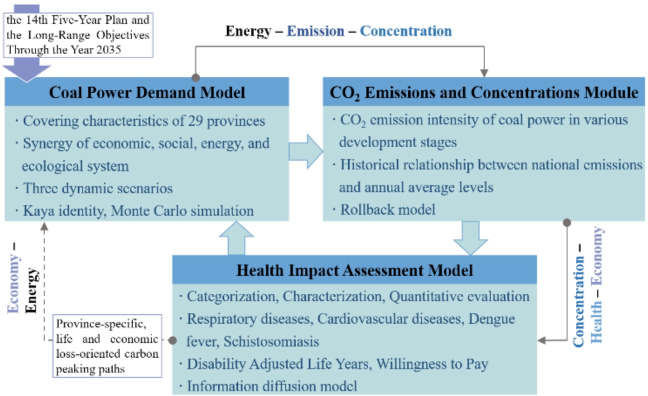

Fig. 1. Model framework proposed in this research

A. *Coal power demand model*

Utilizing the Kaya identity, the coal power demand is divided into two parts of productive and residential needs, which respectively reflect the industrial structure transition in economic development, and the optimization of urban and rural structure in social development, as shown in Eqs. (1)-(4).

$$EI_{GDP}=\frac{E}{GDP}=\frac{E_P+E_R}{GDP} \tag{1}$$

$$\frac{E_P}{GDP}=\frac{E_{PP}+E_{PS}+E_{PT}}{GDP}=\sum\nolimits_{i=1\text{-}3}(S_i\cdot I_i) \tag{2}$$

$$E_R=E_{UR}+E_{RR}=\left(\frac{e_U}{I_U}\cdot\frac{I_U}{gdp}\cdot R_U\cdot POP+\frac{e_R}{I_R}\cdot\frac{I_R}{gdp}\cdot(1\text{-}R_U)\cdot POP\right)\cdot gdp \tag{3}$$

$$E=EI_{GDP}\cdot GDP \tag{4}$$

where EI_{GDP} is coal power consumption per unit of GDP; E is the total coal power consumption; E_P is coal power consumption for productive purposes; E_R is residential coal power consumption; E_{PP}, E_{PS}, E_{PT} are coal power use in the primary, secondary, and tertiary industry, respectively; S_i is the ratio of output value for the three industries, and I_i is the corresponding coal power intensity; E_{UR} and E_{RR} are residential coal power consumption in urban and rural areas, severally; e_U and e_R are residential coal power consumption per capita in urban and rural areas; I_U and I_R are per capita disposable income in urban and rural areas; gdp is per capita GDP; R_U is urbanization rate; POP is the total population.

B. *CO_2 emissions and concentrations module*

CO_2 emissions of coal power generation are computed according to the IPCC guidelines [13], as shown in Eq. (5). Herein, the emission factor for CO_2 of standard coal is referred to the value recommended by the National Development and Reform Commission's Energy Research Institute, and remain constant over time.

$$M=E\cdot\theta\cdot f \tag{5}$$

where M is CO_2 emissions induced by the coal power demand (t); θ is the average coal consumption of power supply (ton of standard coal equivalent / kW·h); f is the emission factor for CO_2 of standard coal, valuing as 2.64 (ton CO_2 / ton of standard coal equivalent).

Rollback model is utilized to estimate change in atmospheric concentrations of criteria pollutants attributed to the estimated emission increments [15], as shown in Eqs. (6) and (7). To exclude the influence of CO_2 background concentration, the Rollback coefficient for CO_2 is fitted in time series in this study, valuing as 1.1519E-05, indicating 1.1519E-05 μg/m^3 increase of CO_2 per ton of emission.

$$C=b+\sum k_iM_i \tag{6}$$

$$\Delta C=\sum k_i\Delta M_i \tag{7}$$

where C is the concentration of criteria pollutants (μg/m^3); b is the background concentration (μg/m^3); k_i is the rollback coefficient of pollutant "i"; M_i is the emission of pollutant "i" which contributes to the added concentrations (t).

C. *Health impact assessment model*

Health impact assessment is proposed to estimate the health damage due to environmental pollution through the variations in health effects of exposed people under specific pollutant concentrations, and obtain the related economic loss in monetized terms [16].

a) Categorization

Exposure to greenhouse gas such as CO_2 and CH_4, mainly pose a severe health threat to humankind through the propulsive effect of global warming-related diseases. Thus, the study selects four types of health damage whose quantitative relationship between global warming and health effects has been identified, to evaluate the health impact caused by CO_2 exposure, namely, respiratory diseases, cardiovascular diseases, dengue fever, and schistosomiasis.

b) Characterization

Effect analysis and damage analysis are conducted. For the former, the added value of the concentrations of environmental pollution is transformed into the increase in the incidence of the related health damage, as shown in Eq. (8). For the latter, the environmental burden of disease for each health damage can be determined by multiplying the number of prevalent cases of the health damage increased by CO_2 exposure and the weight of disability adjusted life year (DALY), as shown in Eqs. (9) and (10).

$$T_j = E_j \cdot C \tag{8}$$

$$DALY_j = YLL_j + YLD_j \tag{9}$$

$$U_j = T_j \cdot DALY_j \tag{10}$$

where T_j is annual added number of cases with health damage "j" (cases/year); E_j is effect factor of health damage "j" caused by CO_2, implying the added cases of health damage "j" caused by CO_2 per unit concentration (cases/(μg·m^{-3}·year)); $DALY_j$ is disability adjusted life year of unit disease case "j" (year/case); YLL_j and YLD_j are years of life lost and years of life with disability for unit disease case "j", respectively (year/case); U_j is added number of DALY with health damage "j" caused by annual emissions of CO_2 (year).

c) Quantitative evaluation

Based on the annual life value of populations (VLY) for American, the value for China is obtained, and thus the environmental burden of disease could be converted to economic loss valuation, as shown in Eqs. (11)-(13).

$$VSL_{target} = VSL_{base} \cdot \left(\frac{GNI\ per\ capita_{target}}{GNI\ per\ capita_{base}}\right)^{elasticity} \tag{11}$$

$$VLY = VSL_{target} \cdot \frac{r}{1-(1+r)^{-n}} \tag{12}$$

$$WTP = U_j \cdot VLY \tag{13}$$

where VSL_{target} and VSL_{base} are the value of VSL for China and the reference country, namely the USA in this study; $GNI\ per\ capita_{target}$ and $GNI\ per\ capita_{base}$ are the gross national income per capita for China and USA, respectively; *elasticity* is the income elasticity factor; *VLY* is annual life value for Chinese people (USD); r is the discount rate, valuing as 4%; n is the remaining years of life (year), valuing as 38.5; *WTP* is willingness to pay, suggesting the cost that people are willing to pay for avoiding the health impact induced by CO_2 exposure (USD).

With respect to the health loss caused by CO_2 exposure, information diffusion model is further applied to further investigate the probability distribution of the estimated health impact cost [17]. (i) Establish a resampling sample. Setting the health impact cost for m years in time series as the observation samples, $X = \{x_1, x_2, \ldots, x_m\}$. And the information diffusion range is $U = \{u_1, u_2, \ldots, u_n\}$, n represents the number of diffusion control points. (ii) Resampling information diffusion. Using the information diffusion methodology, each observation sample is translated into multiple sample points, and the maternal probability density is estimated based on spread function, as shown in Eqs. (14)-(19).

$$f_i(u_j) = \frac{1}{h\sqrt{2\pi}} \exp\left(-\frac{(x_i-u_j)^2}{2h^2}\right) \tag{14}$$

$$C_i = \sum_{j=1}^{n} f_i(u_j) \tag{15}$$

$$\lambda_{x_i}(u_j) = \frac{f_i(u_j)}{C_i} \tag{16}$$

$$q(u_j) = \sum_{i=1}^{m} \lambda_{x_i}(u_j) \tag{17}$$

$$p(u_j) = \frac{q(u_j)}{\sum_{j=1}^{n} q(u_j)} \tag{18}$$

$$P(u \geq u_j) = \sum_{k=j}^{n} q(u_k) \tag{19}$$

where $f_i(u_j)$ is the diffusion function of the sample "i"; x_i is the observed value of the sample "i"; u_j is the domain value of the diffusion control point "j"; h is the diffusion coefficient, which is proposed artificially and derived from the golden section method. In this study, h = 2.6851 × (b-a) / m-1, b and a represents the maximum and minimum value of the observations, respectively. $\lambda_{xi}(u_j)$ is the normalized information distribution of samples; $q(u_j)$ is the number of samples falling within u_j after diffusion; $p(u_j)$ is the frequency value of the sample falling within u_j, representing a probability estimate; $P(u \geq u_j)$ is the probability value that exceeds u_j, representing an exceeding probability estimate.

III. Scenario Setting

A. Study area and basic parameters

Constrained by the *14th Five-Year Plan and the Long-Range Objectives Through the Year 2035* published by provincial governments, the basic parameters for coal power demand forecasting range from 2009 to 2019, which are acquired from the *Provincial Statistical Yearbook*. And the time span for prediction is set as 2020-2035, which is an extrapolation based on the evolutionary regularity of actual values, with the consideration of *provincial urbanization and industrialization policies* embodied in the *14th Five-Year Plan*. Specifically, parameters at four critical times are valued at first, and the rest of the values are assessed using polynomial fitting (refer to TABLE I, taking Beijing as an example). Notably, Ningxia and Tibet are not taken into account owing to data accessibility.

TABLE I. Basic Parameters for Coal Power Demand Forecasting in Beijing

Year	***Population (ten thousand people)***	***GDP per capita (ten thousand CNY)***	***Urbanization rate (%)***	***Industrial structure (secondary: tertiary, %)***
2020	2227	17.67	87.55	15.80: 83.80
2025	2335	21.00	87.98	12.91: 86.86
2030	2449	26.67	88.93	10.02: 89.78
2035	2568	32.00	89.97	7.52: 92.19

B. Scene design and driving factors

Three static scenarios and their dynamic versions following different socioeconomic development paths are established, namely, Baseline scenario (BAS), Rapid development scenario (RDS) and Low-speed development scenario (LDS). As the most likely pattern in the future, the coal power demand and socioeconomic developing level for each province under the BAS scenario follow the past trends.

The specific parameters include coal power intensity for industry (I_1, I_2, I_3), household coal power consumption elasticity for urban and rural areas (e_U/I_U, e_R/I_R), and income elasticity for urban and rural areas (I_U/gdp, I_R/gdp). Compared to the baseline, the RDS and LDS scenarios respectively represent optimistic and pessimistic plan. Under the RDS scenario, the development of coal power sector would conform to more progressive socioeconomic path and more prominent technological advancement. Conversely, the LDS scenario actually represents a high demand plan, the development levels of social, economy and technology are all lower than BAS level, thus resulting an inferior emission reduction potential in coal power. As an illustration, TABLES II and III list the values of driving factors for predicting coal power demand in typical regions.

TABLE II. SCENARIOS OF COAL POWER INTENSITY FOR FOUR TYPICAL REGIONS IN 2035 (UNIT: 10^{-2} KW·H/CNY)

City	***Primary industry***			***Secondary industry***			***Tertiary industry***		
	BAS	RDS	LDS	BAS	RDS	LDS	BAS	RDS	LDS
BJ	7.24	6.74	7.74	4.66	4.16	5.16	1.65	1.35	1.95
HA	1.68	1.18	2.18	7.83	7.33	8.33	0.91	0.61	1.21
CQ	0.15	0.15	0.65	4.52	4.02	5.02	1.16	0.86	1.46
HL	0.49	0.49	0.99	11.6	11.1	12.1	1.99	1.69	2.29

TABLE III. SCENARIOS OF COAL POWER CONSUMPTION ELASTICITY AND INCOME ELASTICITY COEFFICIENTS IN BEIJING

Year	***Urban coal power consumption elasticity coefficient***			***Rural coal power consumption elasticity coefficient***		
	BAS	RDS	LDS	BAS	RDS	LDS
2016-2020	0.84	0.74	0.94	1.83	1.73	1.93
2021-2025	0.78	0.68	0.88	1.73	1.63	1.83
2026-2030	0.67	0.57	0.77	1.63	1.53	1.73
2031-2035	0.57	0.47	0.67	1.53	1.43	1.63
Year	***Urban per capita disposable income elasticity coefficient***			***Rural per capita disposable income elasticity coefficient***		
	BAS	RDS	LDS	BAS	RDS	LDS
2016-2020	0.92	0.94	0.90	0.94	0.96	0.92
2021-2025	0.94	0.96	0.92	0.96	0.98	0.94
2026-2030	0.96	0.98	0.94	0.98	1.00	0.96
2031-2035	0.98	1.00	0.96	1.00	1.02	0.98

Applying Monte Carlo simulation, the static scenarios mentioned above are transformed into dynamic versions with the consideration of uncertainty. Technically, the essence of Monte Carlo simulation is to repeat sampling from several input variable probability distributions to establish the distribution of output variables. Therefore, the dynamic scenarios are constructed using three steps in this study. First, the prior probabilities of critical variables that drive coal power demand in the Kaya identity are defined. Second, 10000 simulations are conducted by distributing a random sample variable range based on the pre-defined probability. Third, the simulation distributions reflecting the projected ranges of coal power variations are obtained.

IV. RESULTS ANALYSIS

A. *Coal power demand forecasting*

It is estimated that the total coal power requirement in China represents a curvilinear rise trend during 2009-2019, with an average growth rate of 5.19% annually. Promoted by the development of industrialization and urbanization, it is forecasted that China's coal power demand would keep going up, no inflection point is observed under three scenarios by 2035. Under the BAS scenario, the projection coal power demand is ranging from 4687.26 billion kW·h in 2020 to 8897.13 billion kW·h in 2035. The growth rate of annual coal power consumption keeps in 3.45%~6.38% under three scenarios. More specifically, Shandong province shows the greatest requirement, valuing as 500.57±138.47, 618.20±126.94, 741.45±123.83, and 894.39±126.74 billion kW·h in 2020, 2025, 2030, and 2035 under the BAS scenario. By contrast, Qinghai province requires for the least coal power, with the values of 5.68±2.22, 7.34±2.17, 8.82±2.05, and 10.58±2.02 billion kW·h in 2020, 2025, 2030, and 2035.

In addition, there is an obvious spatial heterogeneity of coal power demand in China. East China supplies a larger share of the average coal power demand than any other region, whose average is rough 1.43-1.48 times that of the national average. Notably, it is found that Central China is the only region whose share of nation's coal power demand is growing, with the contribution of 21.15%-23.89% (BAS), 20.91%-23.74% (RDS), and 21.30%-23.92% (LDS) during 2020-2035. It is accordance with the national strategic planning in boosting central region, whose rapid socioeconomic development calls for more electric power.

B. *CO_2 emissions forecasting*

Projected CO_2 emissions of coal power generation in three scenarios are assessed. It is found that with the unchanged energy structure and technical conditions, national CO_2 emissions would increase by 65.68% during 2020-2035 relative to the 2015 level. And the RDS emissions reveal a potential carbon emission reduction pathway, with the sum of 76.96 billion tons CO_2 during the projection period. In terms of provincial comparisons, coal power demands of Guangdong, Jiangsu, and Shandong province result in the greatest cumulative CO_2 emissions in the period of 2020-2035, valuing as 72.09±4.03, 81.31±4.36, and 87.01±4.08 at the BAS level (unit: 10^8 tons). In contrast, the smallest emissions cumulated in the projection duration occur at Hainan, Yunan, and Qinghai province under the BAS scenario, with the values of 4.67±0.35, 2.89±0.14, and 1.04±0.07 (unit: 10^8 tons).

The increase of provincial CO_2 concentrations is depicted in Fig. 2. Under the BAS scenario, coal power demand in East China significantly contributes to the CO_2 concentrations, with the sum of 149.47, 156.11, and 190.21 mg/m^3 for the period of 2020-2025, 2026-2030, and 2031-2035, respectively. While West and Northeast China have the least growth, with the average CO_2 concentration decreasing by approximately 56.79% and 66.91% compared with the East China level for each province. Thus, it could be concluded that under the current technical conditions, the situation of CO_2 emissions in coal power industry is still severe, and representing an evident spatial heterogeneity. It is suggested that the formulation of the restriction policies for coal power industry should be principled on "common but differentiated responsibilities", with considering the provincial socioeconomic characteristics.

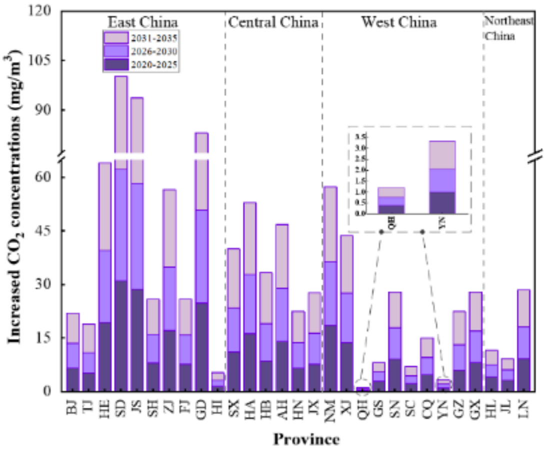

Fig. 2. Projected CO_2 concentrations increment under the BAS scenario

C. *Health impact forecasting*

As a result of CO_2 emissions, it is assessed that there would be 96.1 years of life loss for per 1 ppm increase in CO_2 concentration. Herein, the health damage of respiratory diseases contributes the most, following by dengue fever, schistosomiasis, and cardiovascular diseases. Morbidities of different health outcomes are reduced in RDS scenario compared with the BAS and LDS level, by enhancing the policy to promote the coordinated development in China, the number of avoided life losses could reach to 10539 to the greatest degree, for the whole nation during 2020-2035.

According to the health impact data in monetized terms calculated using Eqs. (11)-(13), three observation samples $X_1 = \begin{pmatrix} 2.39, 2.53, 2.63, 2.74, 2.84, 2.92, 3.08, 3.21, \\ 3.34, 3.48, 3.62, 3.77, 3.92, 4.07, 4.23, 4.39 \end{pmatrix}$, $X_2 = \begin{pmatrix} 2.24, 2.36, 2.46, 2.55, 2.65, 2.72, 2.86, 2.98, \\ 3.10, 3.23, 3.36, 3.49, 3.62, 3.76, 3.91, 4.05 \end{pmatrix}$, and $X_3 = \begin{pmatrix} 2.56, 2.70, 2.82, 2.94, 3.05, 3.14, 3.31, 3.46, \\ 3.60, 3.75, 3.91, 4.07, 4.23, 4.40, 4.57, 4.75 \end{pmatrix}$ are stablished (unit: 10^2 million dollar), representing the total economic loss of CO_2 emissions in Chinese coal power sector from 2020 to 2035, under the BAS, RDS, and LDS scenario. Fig. 3 shows the exceeding probability of the health loss induced by CO_2 emissions from coal power generation, indicating that the estimated risk of total CO_2-related economic losses in Chinese coal power sector decreases as the risk level increases, and the corresponding exceeding probability reduces successively. Specifically, there is approximately a 51.75% probability that the economic loss of new CO_2-related health impact in Chinese coal power sector will exceed 350 million dollars at the BAS level. This suggests that the risk of economic losses induced by CO_2 emitted from coal power generation is not optimistic, and indicates that certain countermeasures should be taken to control the related health impact.

Different from the CO_2 emissions and life loss, which are highly related to the coal power demand in numerical terms for each province, some noteworthy features in the ratio of GDP have been observed and need to be excavated, as shown in Fig. 4. On the one hand, Guangdong, Fujian, and Hubei are three provinces with a great need for coal power in the future, however, their proportions of CO_2-related economic loss to GDP are at a lower level among the investigated 29 provinces, with the ratio of 1.14E-05, 8.61E-06, and 8.46E-06, respectively. On the other, Gansu, Xinjiang, and Inner Mongolia occupy a significant part of economic loss in provincial GDP, valuing as 1.82E-05, 5.02E-05, and 5.45E-05, which are out of proportion to the projected coal power demand and CO_2 emissions. It also reminds us that the formulation of emission reduction targets cannot rely on only single indicator.

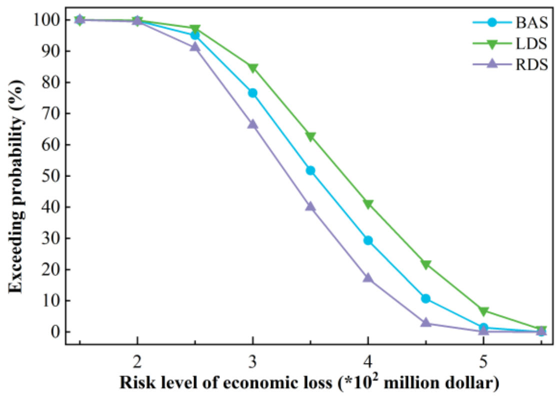

Fig. 3. Exceeding probability of CO_2-related economic loss

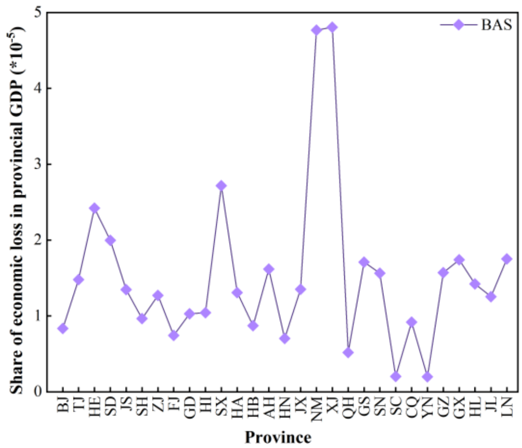

Fig. 4. The ratio of economic loss in provincial GDP during 2020-2035

D. *Low carbon transition strategies*

There are severe challenges for Chinese coal power sector to peak its carbon emissions by 2030. Therefore, it makes great sense to seek for the optimal peaking paths in coal power sector for each of the 29 provinces, which are divided into four categories based on the preceding analysis.

(1) Seven provinces call for less projected coal power, and the related carbon emissions are at low levels. Specifically, economic growth in Jilin and Heilongjiang slowed down in recent years, which has been recognized as a key factor in boosting coal power demand. As for Qinghai, Yunnan, Hainan, Gansu, and Sichuan, renewable energy and new energy contribute to a great share of their electric power structures. Yet, the large-scale of power rationing in Northeast China in September 2021 has indicated the uncertainty of renewable energy generation. Therefore, keeping paces with BAS scenario is a good fit for these provinces, while achieving the long-term stable operation of renewable energy market as soon as possible.

(2) Eight provinces are classified as optimized regions (i.e., Beijing, Shanghai, Tianjin, Chongqing, Guangdong, Jiangsu, Zhejiang, and Fujian), which all have significant coal power demand, meanwhile, are characterized by their diverse industrial structure and state-of-art technology level. In detail, these provinces mainly locate in East China, whose urbanization construction is beginning to stabilize,

and the power structure closest to the level of developed countries. Therefore, it is of vital importance for these provinces that improving energy efficiency, and reducing the dependency on other provinces' coal electricity. For East China, transforming from energy consumers to prosumers with fully utilizing the distributed renewable energy, would not only help to realize carbon emission reduction, but solve the imbalance and inadequate of national energy development.

(3) Five provinces of Central China are identified as high demand in coal power, which is relevant to the strategy to boost central region development. Specifically, Hunan, Jiangxi, Hubei, Anhui, and Henan have entered a new stage of high-quality development. During this period, the accelerating developing of economy and the enhancing of new-type industrialization, are closely bound up with electricity security. Undoubtedly, more carbon emissions would generate from coal power generation with the current technological conditions, therefore, technological innovations such as zero-carbon technology plays an imposing role in emission reduction for Central China. Further, coordinated development of economy, social, and ecology is of uttermost importance in these provinces, which is simultaneously associated with the alternation of power structure from supply side, and the transition of energy utilization behavior from demand side.

(4) The fourth category includes nine provinces with relatively high demand of coal power, most of them are recognized as energy-intensive and resource-rich areas. It should be noted that for these provinces whose fossil energy production is concentrated and the industrial structure tends to heavy industry, carbon peaking goal has a great influence on economic activities. Taking Inner Mongolia as an example, the economic loss of CO_2-related health impact from coal power generation takes up for the greatest ratio in its provincial GDP level, valuing as 5.45E-05 in 2020 under the BAS scenario. Therefore, carbon pricing in these regions must be flexible, with the guiding principles of science, justice, and efficiency. What's more, deepening institutional reform in power industry, and realizing the green and intelligent construction of electricity grid have been generally considered as the vital pathway in emission reduction for these provinces.

V. Conclusions

Coal power provides a safe and reliable support for electricity power in China. By simulating China's coal power demand at the provincial level and assessing the CO_2-related health impact in indicators of life and economic loss, using Kaya identity, health impact assessment model, and Monte Carlo simulation, we found that: (1) China's coal power demand would keep rising by 2035, owing to the development of urbanization and industrialization. Shandong and Qinghai province represent the greatest and least demand respectively, valuing as 767.65-1021.13 and 8.56-12.60 billion kW·h in 2035 under the BAS scenario; (2) An east-west spatial heterogeneity in CO_2 emissions is observed. Specifically, affected by larger population size and advanced economic level, the East China would contribute to more severe carbon emissions. And RDS scenario set in this study reveals a potential carbon emission reduction routine; (3) Life and economic loss of CO_2-related health impact are significant, which could provide more rational references for establishing carbon reduction targets for provincial regions in China; (4) The differentiated mitigation policies based on the characteristics and dynamics of each province would be highly needed to fulfill the ambitious goals to peak emissions in China's coal power sector; meanwhile, considering the flexible application of various policy instruments.

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References

[1] Eyring V, Cox P, Flato G, Gleckler P, Abramowitz G, Caldwell P, et al. Taking climate model evaluation to the next level. Nature Clim Change 2019;9(2):102-110.

[2] Van Soest H, den Elzen M, van Vuuren D. Net-zero emission targets for major emitting countries consistent with the Paris Agreement. Nat Commun 2021;12(1):1-9.

[3] IEA. Global Energy Review: CO_2 Emissions in 2021; 2022. https://www.iea.org/reports/global-energy-review-co2-emissions-in-2021-2.

[4] IEA. An Energy Sector Roadmap to Carbon Neutrality in China. Paris: IEA; 2021.

[5] Khanna N, Fridley D, Zhou N, Karali N, Zhang J, Feng W. Energy and CO_2 implications of decarbonization strategies for China beyond efficiency: Modeling 2050 maximum renewable resources and accelerated electrification impacts. Appl Energy 2019;242:12-26.

[6] Lin J, Fridley D, Lu H, Price L, Zhou N. Has coal use peaked in China: Near-term trends in China's coal consumption. Energy policy 2018;123:208-214.

[7] Li W, Zhang Y, Lu C. The impact on electric power industry under the implementation of national carbon trading market in China: A dynamic CGE analysis. J Cleaner Prod 2018;200:511-523.

[8] Zhang L, Li Y, Jia Z. Impact of carbon allowance allocation on power industry in China's carbon trading market: Computable general equilibrium based analysis. Appl Energy 2018;229:814-827.

[9] Ali H, Sanjaya S, Suryadi B, Weller S. Analysing CO_2 emissions from Singapore's electricity generation sector: Strategies for 2020 and beyond. Energy 2017;124:553-564.

[10] Emodi N, Chaiechi T, Beg A. Are emission reduction policies effective under climate change conditions? A backcasting and exploratory scenario approach using the LEAP-OSeMOSYS Model. Appl Energy 2019;236:1183-1217.

[11] Zhang J, Liu M, Bi J. Urban greenhouse gas emission peaking paths and embedded health co-benefits: A multicases comparison study in China. Appl Energy 2022;311:118740.

[12] Xie Y, Dai H, Xu X, Fujimori S, Hasegawa T, Yi K, et al. Co-benefits of climate mitigation on air quality and human health in Asian countries. Environ Int 2018;119:309-18.

[13] Intergovernmental Panel on Climate Change. Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: The Workbook (Volume 2). (Intergovernmental Panel on Climate Change, 1996).

[14] B. T. Ong, K. Sugiura, K. Zettsu. Dynamically pre-trained deep recurrent neural networks using environmental monitoring data for predicting $PM_{2.5}$. Neural Comput Appl 2016;27(6):1553-1566.

[15] Shih Y, Tseng C. Cost-benefit analysis of sustainable energy development using life-cycle co-benefits assessment and the system dynamics approach. Appl Energy 2014;119:57-66.

[16] Jung S, Kang H, Choi J, Hong T, Park H, Lee D. Quantitative health impact assessment of construction noise exposure on the nearby region for noise barrier optimization. Build Environ 2020;176:106869.

[17] Wang Y, Chen H, Long R, Yang M. Health economic loss measurement and risk assessment of new cases of coal worker's pneumoconiosis in China. Saf Sci 2020;122:104529.