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Managing the phaseout of coal power: A comparison of power decarbonization pathways in Jilin Province

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Abstract: With the periodic goals of reaching carbon emission peak before 2030 and achieving carbon neutrality before 2060 (“dual carbon” goals), China shows its unprecedented determination to coal power phaseout. This research takes Jilin Province to showcase possible pathways of coal power units’ phaseout on provincial level. We set up four different coal power phaseout scenarios, under which their transition cost and effectiveness would be calculated, respectively. In terms of natural resource endowment and electricity demand, Jilin Province would achieve a complete coal power phaseout by 2045 or even by 2040. However, after assessing the effectiveness of power transition under the four coal development scenarios, we found out that the transition costs for the earlier coal power phaseout scenario is CNY 6–47 billion lower than the normal coal power retirement scenario. In addition, after 2040, compared to the normal coal power retirement scenario, the average unit cost of electricity generation for the coal power earlier phaseout scenario is 11–40 CNY/MWh higher. However, the earlier coal power phaseout scenario would save 168 to 220 million tons of coal and reduce 449 – 614 million tons of CO2 emissions, significantly better than the normal coal power retirement scenario. Therefore, a clean transition and achieving the “dual carbon” goal requires a practical course of action that fully considers the power transition's cost-effectiveness and reasonably spreads the transition costs by improving the design of the electricity market mechanism.

Keywords: Carbon neutrality, Coal-fired power, Jilin Province, Phaseout, China

1. Introduction

Climate change is the world's great challenge, and it is urgent to take measures to reduce greenhouse gas emission from fossil fuel (UNFCCC, 2015; IPCC, 2018). Many countries and regions in the world are making efforts for the phaseout or transition of coal power. By the end of 2020, more than 25 countries and regions worldwide have committed to phasing out coal-fired power plants by 2030 (Lauri, 2021). In addition, it is proposed to support coal power phaseout through multiple ways, such as deploying large-scale renewable energy (Hodges, 2018; Duan et al., 2018), controlling the scale of additional coal power strictly (Webb et al., 2020), shortening the service life of coal power (Zhang et al., 2020), retrofitting coal power with CCS devices (Wang et al., 2020), developing large-capacity energy storage (Li et al., 2015), and implementing demand response projects. Jenkins et al. (2018) pointed out that the integrated use of natural gas with CCS devices and renewable energy could completely replace coal power and eventually achieve zero carbon emissions in the power sector globally.

As the country with the world's largest greenhouse gas emission and coal power capacity, China has put forward its “carbon peaking” before 2030 and “carbon neutral” before 2060 goals (BBC, 2020). Accounting for nearly 40% of the total energy sector emissions, China's power sector low-carbon transition during the 14th Five Plan Year (FYP) period (2021–2025) and beyond will play a deciding role in realizing China's “dual carbon” goals.

In March 2021, China announced to form a clean, low-carbon, safe and efficient energy system, control the total amount of fossil energy, improve the energy use efficiency, replace traditional energy with renewable energy, deepen the power system reform, and build the new power system with new energy as the core. In April 2021, it is announced that China will “strictly control” the building of new coal-fired power plants in the 14th FYP period (2021–2025), and will begin reducing the size of the coal-fired fleet in the 15th FYP period (2026–2030) (Xinhua Net, 2021). Therefore, it shows the government's aggressiveness to take additional policy measures to restrict coal power expansion. However, due to the high price of coal used for power generation, some places in the three provinces in Northeast China, including Heilongjiang, Jilin, and Liaoning, are experiencing electricity shortages. Extreme cut-off of coal might also cause the collapse of the local power grid, worsening the regional power shortage (BBC, 2021).

Based on a database of coal-fired power plants in China, Cui et al. (2021) developed a metric using Global Change Assessment Model (GCAM) to determine the roadmap for early phaseout of coal-fired power plants in China. The paper also amplifies the feasibility of meeting China's 2060 carbon neutrality goal and the global 1.5 °C climate goal. According to Kahrl et al. (2021), with renewable energy and energy storage deployment, China could achieve zero coal power generation by 2040. However, this study didn't include transition costs. Meanwhile, previous analysis of power transition in China and beyond has focused on the financial implications of asset stranding (Mo et al., 2021a; Zhang et al., 2021; Pfeiffer et al., 2018). In addition, most studies have only assessed the long-term power transition costs for developed countries. Study of the UK considered only the investment costs, fixed and variable O&M costs, fuel costs, financing costs, and carbon price (Trutnevyte et al., 2015). Li and Trutnevyte (Li and Trutnevyte, 2017) explored 800 future transition pathways for the UK power sector explored under uncertainty, and the analysis found that achieving climate targets may require additional investments of £35bn–£80bn. Kim (2018) explored the environmental and economic implications of South Korean electricity sector changes using the Long-range Energy Alternative Planning model. What's more, Oyewo et al. (2020) assessed the cost of electricity for the West African power sector from a long-term perspective by the LUT model. However, no existing papers have analyzed the cost-effectiveness of coal power phaseout at the provincial level in China. The study in this paper will add to the literature on this point.

Jilin province, as one of the first industrial bases in China, is facing an urgent coal power phaseout problem compared to other provinces due to the rapid growth of renewable energy, the serious erosion of coal power economics, and the strong demand for heat supply (Yuan et al., 2019). Therefore, this paper takes Jilin province, a typical fossil fuel-based province in northern China, as an example to study the provincial coal power phaseout pathway. We calculated the transition costs under different strategies in which emitting coal power plants would continue to retire at the current or an accelerated pace and build a series of affordable clean energy and design climate mitigation solutions. The study of coal power phaseout in Jilin Province would optimize the provincial action plan for power transition, provide a reference for provinces with heating demand, and set up an example of the decarbonization of the power sector.

We will discuss the methodology in Section 2, the current state and various scenarios modeling coal power in Jilin Province in Section 3, the result of the transition cost-effectiveness in Section 4, with policy implications at the end of the paper.

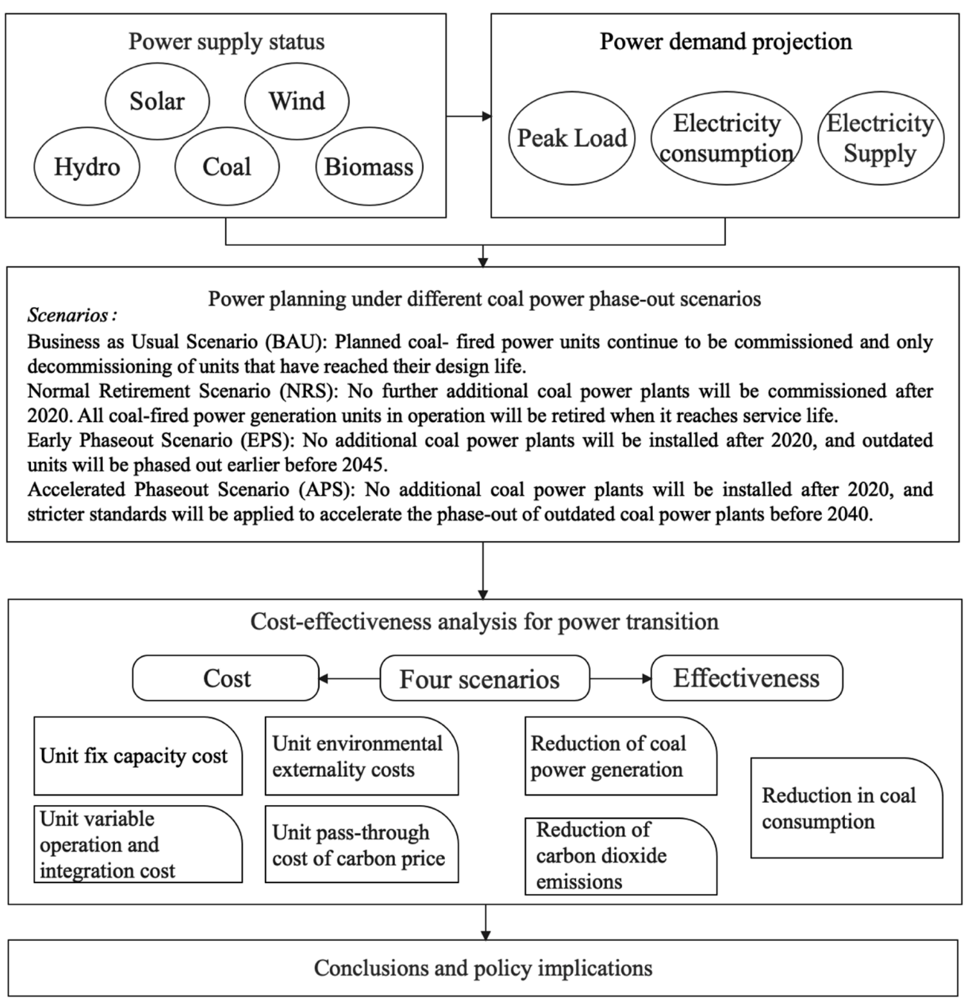

Fig. 1. The framework for our research.

2. Methodology

2.1. Analytic framework

The procedure of the analysis is shown in Fig. 1. Firstly, based on historical data, we analyzed the economic development situation to obtain the power demand of Jilin Province from 2021 to 2050. Secondly, we used the electric power and energy balance model (Feng et al., 2018) to analyze the future power planning of Jilin Province based on different coal power phaseout scenarios. We analyzed the possible phaseout pathways of coal power under different scenarios from 2021 to 2050, and evaluated the transition cost-effectiveness under different scenarios. Finally, based on the cost-effectiveness comparison, we provided policy implications for the low-carbon power transition in Jilin Province.

2.2. The electric power and energy balance model

The electric power and energy balance is the basis of power system operation. Based on the actual operation mode of power system, indexes such as types and utilization hours of power plants, electricity consumption and load on provincial level, and inter-province power/energy exchange should be included in the evaluation model. The model detail is as follows.

Constraint 1: Energy balance

$$\sum_{n=1}^{i}\left(Ca_{y,i}^{m}\times H_{y,i}^{m}\right)+W_{y,in}^{m}-W_{y,out}^{m}-W_{y,ec}^{m}\times(1+R_{l})\geq 0\ (i=1,2,\ldots,8) \quad (1)$$

In Eq. (1),

$Ca_{y,i}^{m}$: the installed capacity of power under the scenario m in year y, including coal power, gas power, hydropower, wind power, solar energy, nuclear power, pumped storage and biomass power, denoted as $C_1 \ldots C_8$(kW);

- $H_{y,i}^{m}$: the utilization hour of coal and other types of power sources under the scenario m in year y, denoted as $H_1 \ldots H_8$(h);
- $W_{y,in}^{m}$ and $W_{y,out}^{m}$: the equivalent energy import/export of inter-province exchange under the scenario m in year y, it is a fixed consideration in this paper (kWh);
- $W_{y,ec}^{m}$: the electricity consumption under the scenario m in year y (kWh);
- R_l: the loss and self-use ratios, it is set to 10% in this paper.

Constraint 2: Electric power balance

$$\sum_{n=1}^{i}\left(P_{y,i}^{m}\times \alpha_{y,i}^{m}\right)+P_{y,in}^{m}-P_{y,out}^{m}-P_{y,dr}^{m}-P_{y,pl}^{m}\times(1+R_{r})\geq 0\ (i=1,2,\ldots,8) \quad (2)$$

In Eq. (2),

- $\alpha_{y,i}^{m}$: the resource adequacy value of coal and other types of power sources, denoted as $\alpha_1 \ldots \alpha_8$ (%);
- $P_{y,i}^{m}$: the installed capacity of coal and other types of power sources, denoted as $P_1 \ldots P_8$ (kW);
- $P_{y,in}^{m}$ and $P_{y,out}^{m}$: the equivalent import and export power of inter-province exchange under the scenario m in year y, it is a fixed consideration in this paper (kW);
- $P_{y,dr}^{m}$: the demand response load under the scenario m in year y (kW);
- $P_{y,pl}^{m}$: the peak load under the scenario m in year y (kW);
- R_r: the reasonable reserve ratios, it is set to 15% in this paper.

Once these two constraints are satisfied, the electricity consumption and peak load supply could be balanced.

2.3. Methodology of power transition cost-effectiveness

The transition cost of power plants includes four metrics: the unit fix capacity cost, the unit variable operation and integration cost, the unit external costs, and the pass-through cost of carbon price. The transition effectiveness of power plants mainly considers the reduction of three aspects: electricity from coal-fired power, coal consumption for coal-fired power, and carbon dioxide emissions from coal-fired power.

2.3.1. Total transition cost of power plants

The total transition cost of power plants refers to the comprehensive cost input for power development during 2021–2050, including fixed and operation cost of power supply capacity. In this model, power plants refer to the accumulative amounts of hydro, thermal, nuclear, wind, and solar power. It considers the negative external costs caused by coal, gas, and biomass power. In addition, the paper also considers the integration costs associated with new energy generation and the pass-through cost of carbon price.

$$C_{Gen}^{m}=\sum_{y}\left(C_{y,fix}^{m}+C_{y,var}^{m}+C_{y,ext}^{m}+C_{y,car}^{m}\right) \quad (3)$$

In Eq. (3),

- C_{Gen}^{m}: the total transition cost of power plants;
- $C_{y,fix}^{m}$: the annualized fixed capacity cost under the scenario m in year y;
- $C_{y,var}^{m}$: the annual variable operation and integration cost under the scenario m in year y;
- $C_{y,ext}^{m}$: the external costs under the scenario m in year y;
- $C_{y,car}^{m}$: the pass-through cost of carbon price under the scenario m in year y, unit is CNY.

$$C_{y,fix}^{m}=\sum_{i}\left(C_{y,i,fix}^{m}\times Ca_{y,i}^{m}\right) \quad (4)$$

In Eq. (4),

- $C_{y,i,fix}^{m}$: the per unit annual fixed capacity cost of power source i under the scenario m in year y (CNY/kW•year);
- $Ca_{y,i}^{m}$: the installed power supply capacity i under the scenario m in year y (kW).

Based on the economic parameters of fix capacity cost and variable operation and integration cost for various power resources created by Zhu et al. (2021), we further considered the learning effect of technological progress in cost reduction. The investment costs of power plants are included in the fixed capacity costs and are also annualized according to the design life of the different types of power units. With the increasing cumulative installed capacity, the effect of "learn by doing" was continuous accumulation, and the production efficiency constantly improved, leading to the decreasing fixed capacity costs and variable operation costs for power technology (Xu et al., 2017; Tu et al., 2019, 2020; Liu et al., 2020). Based on reasonable assumptions about the future installed capacity of different power generation technologies, a learning curve model was used to calculate the learning rates of solar and wind power technologies in China, which are 18.3% and 7%, respectively (Yin and Chen, 2012). Meanwhile, Kittner et al. (2017) calculated a learning rate of 15.47% for the battery storage.

$$C_{y,var}^{m}=\sum_{i}\left(C_{y,i,ope}^{m}\times Ca_{y,i}^{m}\times H_{y,i}^{m}\right)+\sum_{i}\left(C_{y,i,int}^{m}\times Ca_{y,i}^{m}\times H_{y,i}^{m}\right) \quad (5)$$

In Eq. (5),

- $C^m_{y,i,ope}$: the per unit variable operation cost of power supply i under the scenario m in year y (CNY/kWh);
- $C^m_{y,i,int}$: the per unit variable integration cost of new energy power supply i under the scenario m in year y (CNY/kWh);
- $H^m_{y,i}$: utilization hours of power source i under the scenario m in year y (hour).

Variable operation costs for coal and gas-fired power generation are assumed to increase by 2% per year, considering changes of fuel prices (Yuan et al., 2017; Zhao et al., 2017). Meanwhile, the external environment greatly affects variable renewable energy (VRE) and has certain variability and unpredictability. Therefore, with the increasing penetration rate of VRE in the future, the measures taken to consume VRE will increase the extra cost of the system. The additional cost of power system is the variable integration cost of VRE (Ueckerdt et al., 2013). In thermal systems, a high penetration rates for new energy market share of 30%–40%, the variable integration costs are found to be 0.18–0.25 CNY/kWh, ie. up to 50% of generation costs (Hirth et al., 2015; Chen et al., 2020). Based on the results from Hirth et al. (2015), we fitted the integration costs of new energy under different penetration rates, as shown in Appendix Fig. B1. Therefore, a variable integration cost of new energy is given in this paper to assess the additional costs.

$$C^m_{y,ext} = \sum_i \left(w_i \times Ca^m_{y,i} \times H^m_{y,i} \right) \tag{6}$$

In Eq. (6),

w_i: the external costs per unit of power source;

i: refers to coal power and gas power (CNY/kWh).

External costs are the unaccounted and uncompensated cost of a production process imposed on society or the environment that are not reflected in market pricing (Owen, 2006). The environmental externality costs of burning fossil fuels for power generation consist of two main components: First, the cost of damage to health and the environment caused by pollutant emissions (including SO_2, NO_x, and $PM_{2.5}$). Second, the cost derived from the impact of climate change due to greenhouse gas (GHG) emissions, which are mainly CO_2 emissions during the combustion of fossil energy (Wang et al., 2018). Wang et al. (2019) estimated that the external cost of coal-fired power in China is 0.17 CNY/kWh on average, substantially higher than biomass power (0.06 CNY/kWh). This paper assumes that the externality cost of the gas-fired unit is 50% of that of the coal-fired plant. It considers the cost of CO_2 emissions generated from coal and gas power generation but does not consider the CO_2 emissions generated during the manufacture of each type of unit.

$$C^m_{y,car} = \sum_i \left(P_{CO_2} \times Ca^m_{y,i} \times H^m_{y,i} \times \left(F_{CO_2,i} - F^B_{CO_2,i} \times Q_{Free} \right) \right) \tag{7}$$

In Eq. (7),

- P_{CO_2}: the carbon price (CNY/ton);
- $Ca^m_{y,i}$: the installed power capacity of power supply i under the scenario m in year y (MW);
- $H^m_{y,i}$: the utilization hours of power supply i under the scenario m in year y (hour);
- $F_{CO_2,i}$: the CO_2 emissions intensity of power supply i (g CO_2/kWh);
- $F^B_{CO_2,i}$: the CO_2 emissions intensity baseline of power supply i (g CO_2/kWh);
- Q_{Free}: ratio of free carbon allowances (%).

In the practice of carbon emission trading, the carbon emission permits can be allocated to the entity by free allocation, partial auction, or full auction (Goulder et al., 2010). MEE (2020) pointed that all allowances in 2019–2020 are allocated free of charge, and the allowance quantity of the units owned by major emitting entities is calculated by the baseline method. The allowance quantity of a major emitting entity is the sum of the allowance quantities for all its types of units. 2019–2020 carbon emission baselines are also given for various units. With the unified nationwide carbon pricing being implemented, the carbon prices in China are expected to converge at a common level, which may lie between 0 and 350 CNY/tCO_2 in the future based on the experiences of the pilots and state trends (Mo et al., 2021b; Ramstein et al., 2019; Slater et al., 2020). Meanwhile, carbon allowances will gradually shift from free allocation to auction. The decrease in coal consumption for electricity supply and emission intensity of CO_2 will also lead to a gradual decrease in the emission intensity baseline of CO_2 (Zhang et al., 2021). With the implementation of the carbon market, the carbon price will be passed on to the electricity price, making the electricity generation cost of coal power rise (Sijm et al., 2006; Bonacina and Gulli, 2007). Sijm et al. (2006) remind us that under perfect competition, the pass-through rate of carbon cost should be 100%, and the additional costs are defined as the pass-through cost of carbon price.

The economic parameters of power supply in key years are shown in the Appendix Table A1-A5. The appraisal methodology is based on an accounting framework with nominal prices (Bhattacharyya and Timilsina, 2010) with one-year time resolution from 2021 to 2050, same as below.

2.3.2. *The transition effectiveness of power plants*

$$R^m_{CP,y,Gen} = Ca^m_{CP,y} \times H^m_{CP,y} - Ca^{BAU}_{CP,y} \times H^{BAU}_{CP,y} \tag{8}$$

In Eq. (8), $R^m_{CP,y,Gen}$: represents the reduction in coal power generation under the scenario m in year y (kWh).

$$R^m_{CP,y,Coal} = R^m_{CP,y,Gen} \times I_{cc} \tag{9}$$

In Eq. (9),

$R^m_{CP,y,Coal}$: the reduction in coal consumption under the scenario m in year y (tons);

I_{cc}: coal consumption (g/kWh).

$$R^m_{CP,y,CO_2} = R^m_{CP,y,Gen} \times I_{CEI} \tag{10}$$

In Eq. (10),

- R^m_{CP,y,CO_2}: the reduction of CO_2 emissions from coal power under the scenario m in year y (tons);
- I_{CEI}: the CO_2 emission intensity of coal power (g/kWh).

3. Current state and modelled scenarios

3.1. *The state of coal-fired power in Jilin Province*

The power supply structure of Jilin Province was relatively simple. Coal power has long been an important source of electricity, with coal power taking up more than 50% during 2005–2020, as shown in Fig. 2. By 2020, Jilin had a total installed power generation capacity of 34 GW, including 5.78 GW wind power and 3.38 GW solar power. With the rapid development of wind and solar power (new energy), the proportion of new energy in the installed power generation capacity increased from 11% in 2010 to 27% at the end of 2020, while the proportion of coal power only decreased from 68% to 56%.

By 2020, Jilin Province had 20.76 GW coal-fired power plants, including 18.91 GW (108 units) in operating service and 1.85 GW (38 units) in planned service. 79% of the operating units are small-capacity with 300 MW and below, as shown in Fig. 3. The vast majority of coal power units in Jilin Province are state-owned assets, which belong to the state-owned power groups: China Energy Investment Corporation (CHN Energy), the State Power Investment Corporation (SPIC), China Huaneng Group Co., Ltd. (CHNG), and China Datang Corporation Ltd. (CDT). CHN Energy has the largest installed coal power unit (5.58 GW). The planned coal power capacity is mainly concentrated in other power

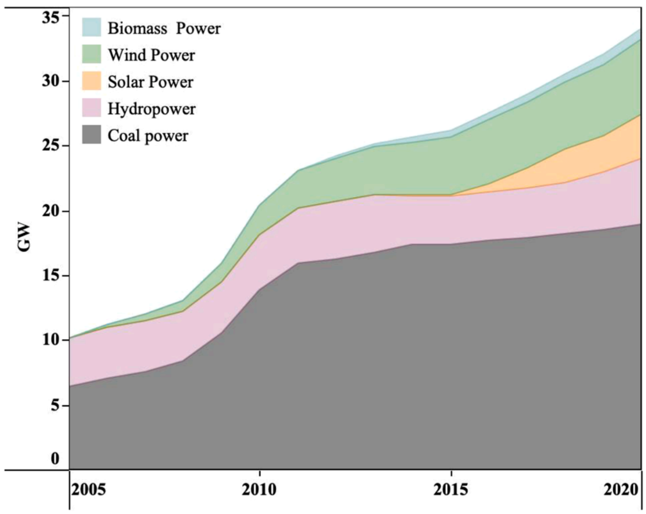

Fig. 2. Power supply capacity mix in Jilin Province during 2005–2020.

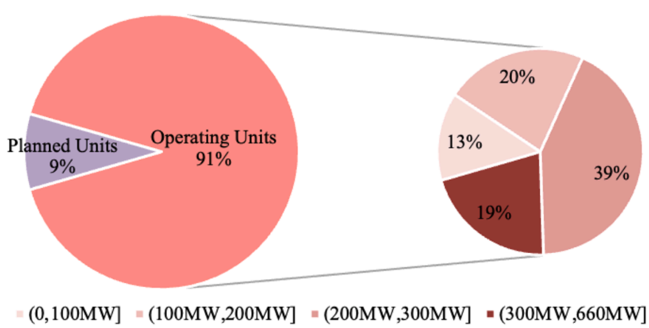

Fig. 3. Structure of coal- fired power capacity in Jilin Province.

generation enterprises other than those mentioned above. The individual capacity of coal power units of other power generation enterprises is generally below 100MW.

Most of the units in Jilin province have high emission level, intensive coal consumption, and long service time. 32% of the operating coal-fired power units are supercritical, and the rest are subcritical. There are no ultra-supercritical or other advanced units, no 1000 MW and above large capacity units available in the province. In terms of unit emissions, 28 of Jilin's operating coal-fired power units exceed the national emission constraint, among which 24 units emit sulfur dioxide and 9 units emit nitrogen oxides that exceed the national limit (Yuan et al., 2019). 58.6% of coal power units in the province consume more coal than the national average level in 2020 (306 g/kWh). More than half of those units are

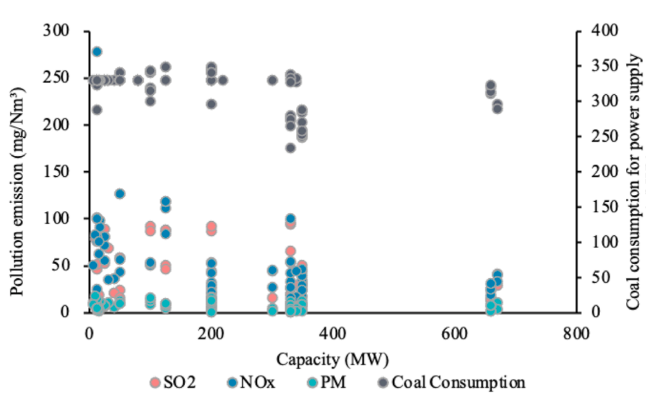

Fig. 4. Emission and energy consumption of coal power units in Jilin Province.

below 300MW, as shown in Fig. 4. Due to its geographical condition and climate, Jilin Province has a long heating cycle with over 70% CHP units. However, its coal power utilization hours have been declining year on year, and in 2019, the unit utilization rate was only 43%. By 2020, 58% of the capacity of coal-fired power units in Jilin Province had operated for more than ten years, as shown in Fig. 5.

3.2. *Modelled scenarios*

To achieve the carbon neutrality goal, we designed models under four scenarios to analyze the possible pathways of phaseout backward operating coal power units, with different retirement years for each coal-fired power units:

Business as Usual Scenario (BAU) refers to planned coal-fired power units continuing to be commissioned and only decommissioning units that have reached their 30 years of design service life.

Normal Retirement Scenario (NRS) refers to canceling planned coal power projects. No further additional coal power plants will be commissioned after 2020. It was necessary to produce this scenario to reflect the reality of "strictly controlling" the building of new coal-fired power plants to assess the implications of the phaseout policy options. Meanwhile, coal-fired power units in operation will be retired when it reaches design service life.

Early Phaseout Scenario (EPS) refers to canceling planned coal power projects. No additional coal power plants will be installed after 2020, and outdated units will be phased out earlier. In this scenario, most units are retired at the end of 2045.

Accelerated Phaseout Scenario (APS) refers to canceling planned coal power projects. No more coal power will be installed after 2020, and stricter standards will be applied to accelerate the phaseout of outdated coal power plants. In this scenario, most units are retired at the end of 2040.

4. Results

4.1. *Forecast of power supply*

We take 2020 as the base year to set up the Jilin power transition plan. According to the historical economic development and electricity consumption analysis in Jilin Province (see Appendix Table A6), we projected the electricity supply and demand of Jilin Province in key years during 2021–2050 (see Appendix Table A7). It is estimated that the future economic situation of Jilin is relatively depressed, with the insufficient endogenous impetus for economic growth, weak growth in electricity demand, and a slightly lower growth rate of electricity consumption than the national average level.

The total social electricity consumption and peak load in Jilin Province are 80.5 TWh and 12.25 GW in 2020, respectively. In order to meet the heating demand of Jilin Province in the future, centralized heating (cogeneration of heat and power), natural gas heating, and electric heating (mainly air source heat pump, regenerative electric

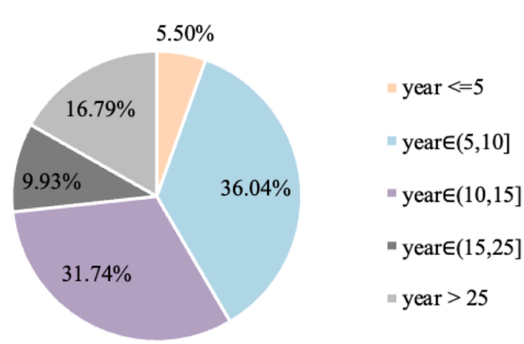

Fig. 5. Operation years of Jilin coal-fired power units by 2020.

heating) will coexist for a long time. Due to the gradual phaseout of coal-fired power units, the proportion of centralized heating will gradually decrease and be replaced by electric heating in the future, greatly increasing the electricity demand. Therefore, the total social electricity consumption and peak load in Jilin Province will be 168.5 TWh and 24.44 GW in 2050, respectively. The forecast electricity demand results for Jilin Province for the key years are shown in Fig. 7.

Fig. 6

In terms of power supply, renewable energy power generation has great potential for development, and it will be the main supplier of future power capacity increase, while the growth of non-renewable energy power capacity is limited. Among the renewable energy resources, wind and solar energy resources are abundant and have a large development space in Jilin Province. The theoretical resource potential of wind power can reach 106.7 GW (China National Renewable Energy Centre CNREC, 2019), and the resource potential of photovoltaic power is 78.2 GW. Wind power and solar power will become the main power supply in Jilin Province in the future. Biomass power generation has a great potential to grow due to the abundant agricultural, forestry, and animal husbandry leftovers in the province. Jilin province has also developed many hydropower projects. However, the development has now reached the bottleneck. Furthermore, the high cost of gas power makes it difficult to become a major project. Jilin is expected to start developing nuclear power to guarantee the heat supply (Reuters, 2019).

4.2. Decarbonization pathways for the power sector

Based on the four different coal power development scenarios, the priority is to utilize renewable energy resources such as wind and solar power. According to the electricity power and energy balance model, we obtained the installed capacity, and annual generation mixes for Jilin Province from 2021 to 2050 in each of the four scenarios, as shown in Fig. 8 and Fig. 9. Under the BAU scenario in which new coal power plants were continuously being built, Jilin's power system will reach its carbon peak in 2022. However, if no additional coal power plants are built, under the NRS, EPS, and APS scenarios, Jilin's power sector could reach its carbon peak by 2020. Meanwhile, under the EPS and APS scenarios, Jilin's power system will phase out the coal power by 2045 and 2040, respectively. In the APS scenario, coal power capacity will fall to zero by 2040, while under the NRS scenario, coal power capacity still maintains around 7.86 GW for reliability (reserve) needs. In the APS scenario, the annual generation of coal power will fall to zero in 2040. However, by then, NRS scenario still has 40.16 TWh/yr.

Jilin Province has abundant wind and solar resources. Considering the power resource conditions and system supply reliability, under the APS scenario, if immediately stop building new coal power and accelerate the coal power phaseout, the power system could reach a carbon emission peak in 2020 and achieve carbon neutrality in 2040, showing significant progress for the energy transition. The capacity and generation of renewable energy power units in the energy mix under the APS scenario could reach 63% and 50% in 2040, respectively, which is more in line with the expectation of a "new type of power system with variable renewables energy (VRE) at the center" (China Dialogue, 2021). In order to verify that the four planning scenarios can meet the real-time power balance on a typical day, we conducted a 24-hour time-series simulation based on the UC model with the dispatch of a typical day for Jilin Province in 2040. The hourly operation results of the Jilin power grid under the four scenarios are shown in Appendix Fig. B2–B5, which shows that the four planning scenarios can guarantee a reliable supply of electricity. The early and accelerated coal power phaseout scenarios require more battery storage installation. However, the choice of action options for a low carbon transition of the power sector must be based on the installed capacity mix of power sources to meet the electric power and energy balance and on comparing the differences in the cost-effectiveness of various power planning scenarios.

4.3. Transition cost-effectiveness

4.3.1. Total transition cost of power plants

Based on the development of various types of power resources in Jilin Province, the total transition cost of power plants under the four scenarios was analyzed and compared, taking into account the fixed and variable costs of power plants and the external and carbon price pass-through costs.

- Costs related to coal power generation

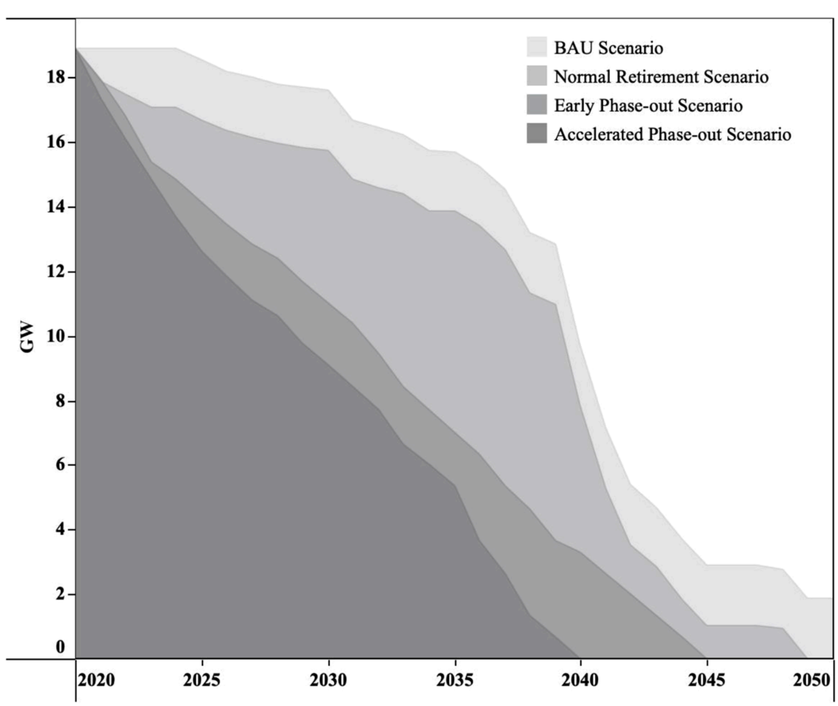

Fig. 6. The development pathway of coal power in Jilin Province under different scenarios.

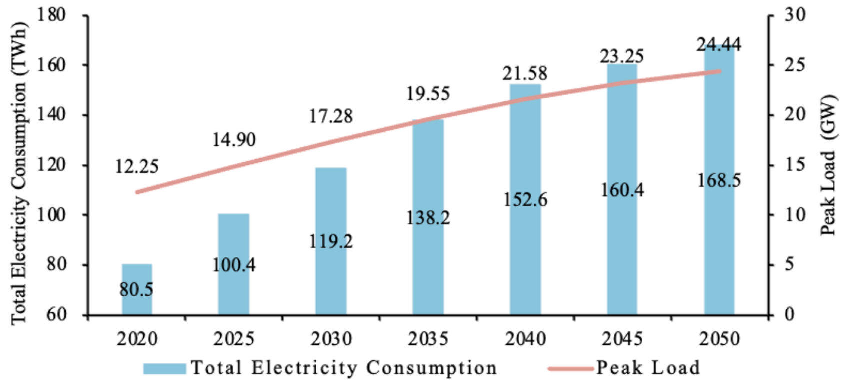

Fig. 7. Forecast result of power demand in Jilin Province from 2020 to 2050.

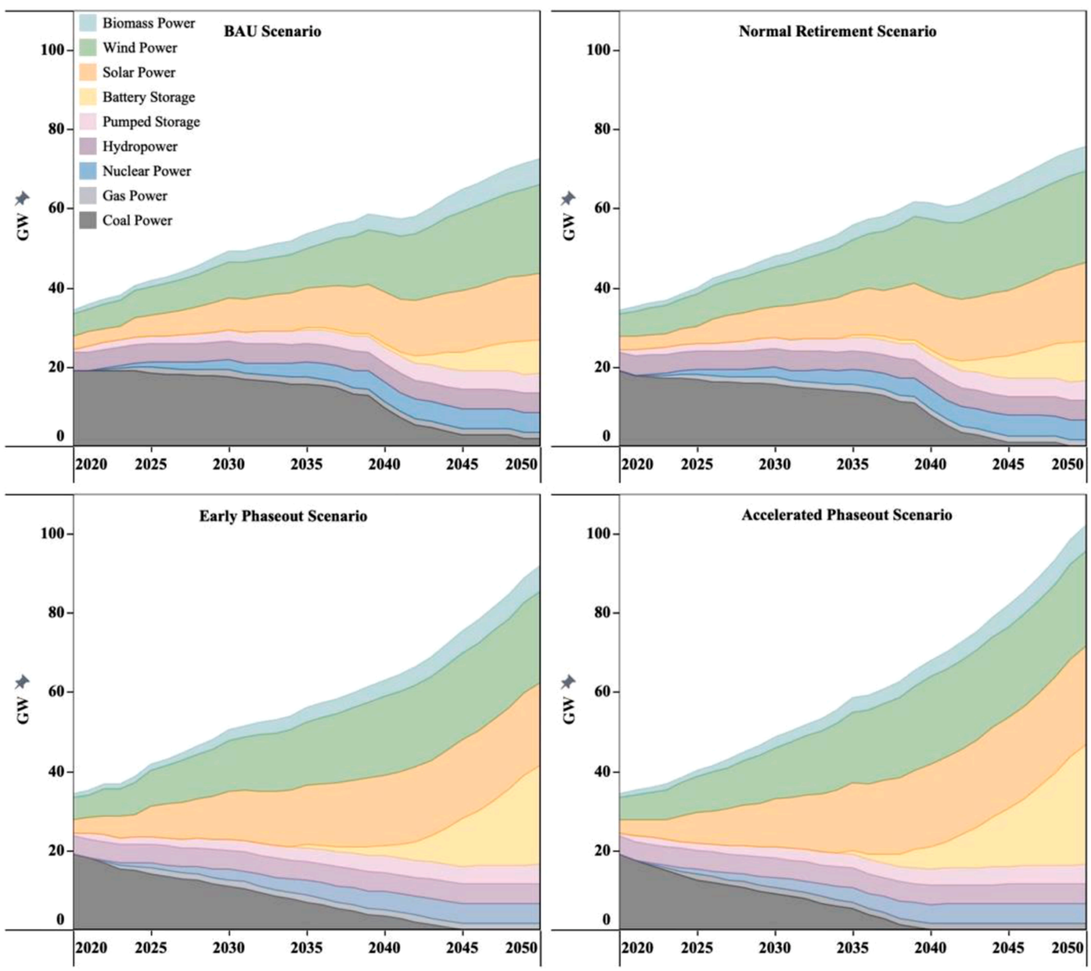

Fig. 8. Installed capacity mix during 2020–2050 under different scenarios.

The related costs of coal power mainly consist of annualized fixed cost, annualized variable cost, external costs of pollution emissions, and carbon price pass-through costs. Since the BAU scenario and the NRS do not have an early phaseout of coal power, the coal power installed capacity is relatively high, and the external costs of pollution emissions and carbon price pass-through costs associated with coal power are gradually increasing in share of the total costs, as shown in Fig. 10. At the same time, many coal plants bring high variable costs of electricity generation. As a result, the costs associated with coal power are much higher in these two scenarios than in the EPS and APS scenarios. Considering the external costs of emissions and carbon price pass-through costs, under the EPS and APS scenario, effective micro phaseout measures for coal power generation can effectively reduce the cost pressure caused by power transition.

Under the EPS and APS scenario, the annualized costs related to coal power would fall to CNY 19 and 15 billion in 2035, respectively, 46% and 37% of the BAU scenario for the same period. However, we must notice that the APS scenario has a steep downward curve in coal power-related costs between 2020 and 2035, creating more pressure on the coal power phaseout, which would cause a high unemployment rate and other social impacts. Although there might be an increase in the number of job opportunities in the renewable industry, the depression in the coal

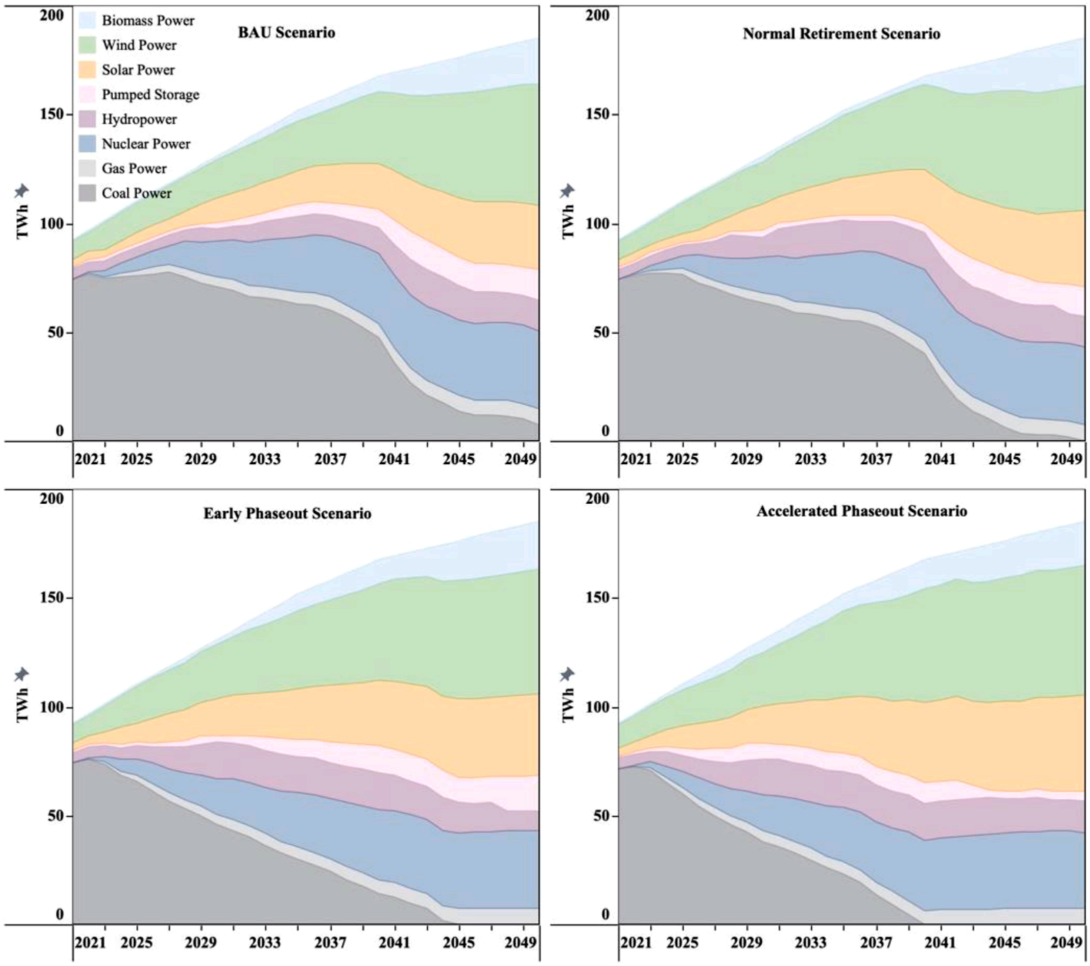

Fig. 9. Annual generation mix during 2021–2050 under different scenarios.

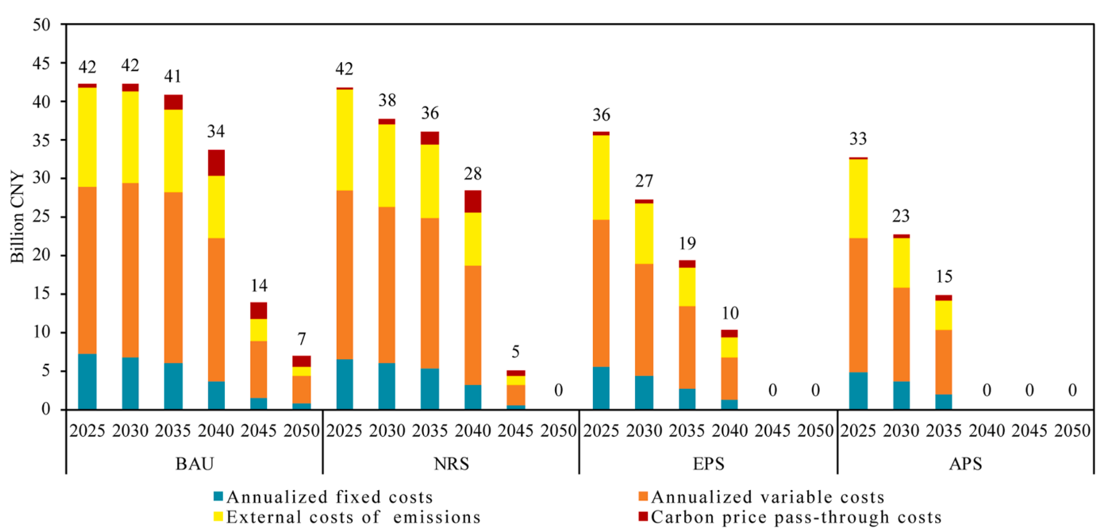

Fig. 10. Annualized generation costs related to coal power in key years under four scenarios.

industry and prosperity in the renewable industry do not necessarily occur in the same geographic region and at the same time (Caldecott et al., 2017). From 2035 to 2045, due to the decommissioning of many coal-fired power plants, the external costs of emissions and carbon price pass-through costs of various scenarios will decrease rapidly. By 2045, the coal power units under the EPS and APS scenario will fall to zero, and the coal power-related costs in that year will be zero, while the costs under the BAU scenario will be as high as CNY 14 billion. It sees that proactive actions could effectively reduce the negative external costs caused by coal power. However, given the job changes and unemployment that will result from the phasing out of coal power, it is also necessary to provide welfare to help job reallocation.

- Annualized generation cost of power plants

We projected the annualized generation cost of power plants under each scenario, and the results show that the BAU scenario, which continues to build new coal power, has a higher amount of coal-fired power output. Therefore, the annualized generation costs are higher in the BAU scenario than in the other scenarios for the period 2021–2040, and the lowest annualized generation costs are found in the APS scenario for the period 2021–2034 and the EPS scenario for the period 2035–2040, as shown in Fig. 11. The APS scenario aims to maximize the consumption of new energy sources such as wind and solar, with a total installed capacity of wind and solar power will reach 49 GW by 2050. The higher investment and integration costs will lead to a rapid increase in annual generation costs under the APS scenario after 2040.

- Total generation cost of power plants

The total electricity generation cost for each scenario calculated from the cumulative annualized cost from 2021 to 2050, as shown in Fig. 12. The result confirm that the power transition towards RE-based systems is possible and affordable in economic and energetic terms. The total generation cost in the BAU scenario is 2490 Billion CNY, much higher than the other three scenarios. Meanwhile, despite achieving an accelerated phaseout of coal power, the APS (no coal power by 2040) scenario still has a higher transition cost than the EPS scenario of 41 Billion CNY. The EPS scenario achieves a competitive transition result with the lowest total generation cost, i.e., large-scale coal power units could be phased out earlier (no coal power by 2045), and more new wind and solar power plants can be installed.

- Uncertainties and sensitivity analysis

Multiple uncertainties may affect the transition of power systems and their costs. First, in terms of investment costs, the learning rate changes for wind, PV, battery storage are uncertain, and new energy sources would become competitive if there were a rapid technology learning effect. In reality, the cost of capital may vary substantially between different technologies, and differences in generation and end-use technologies may lead to greater variability in investment costs, which can significantly affect total transition costs. Second, varying fuel costs can make an important difference in operating costs in terms of variable costs. Meanwhile, some research still shows that some low-carbon

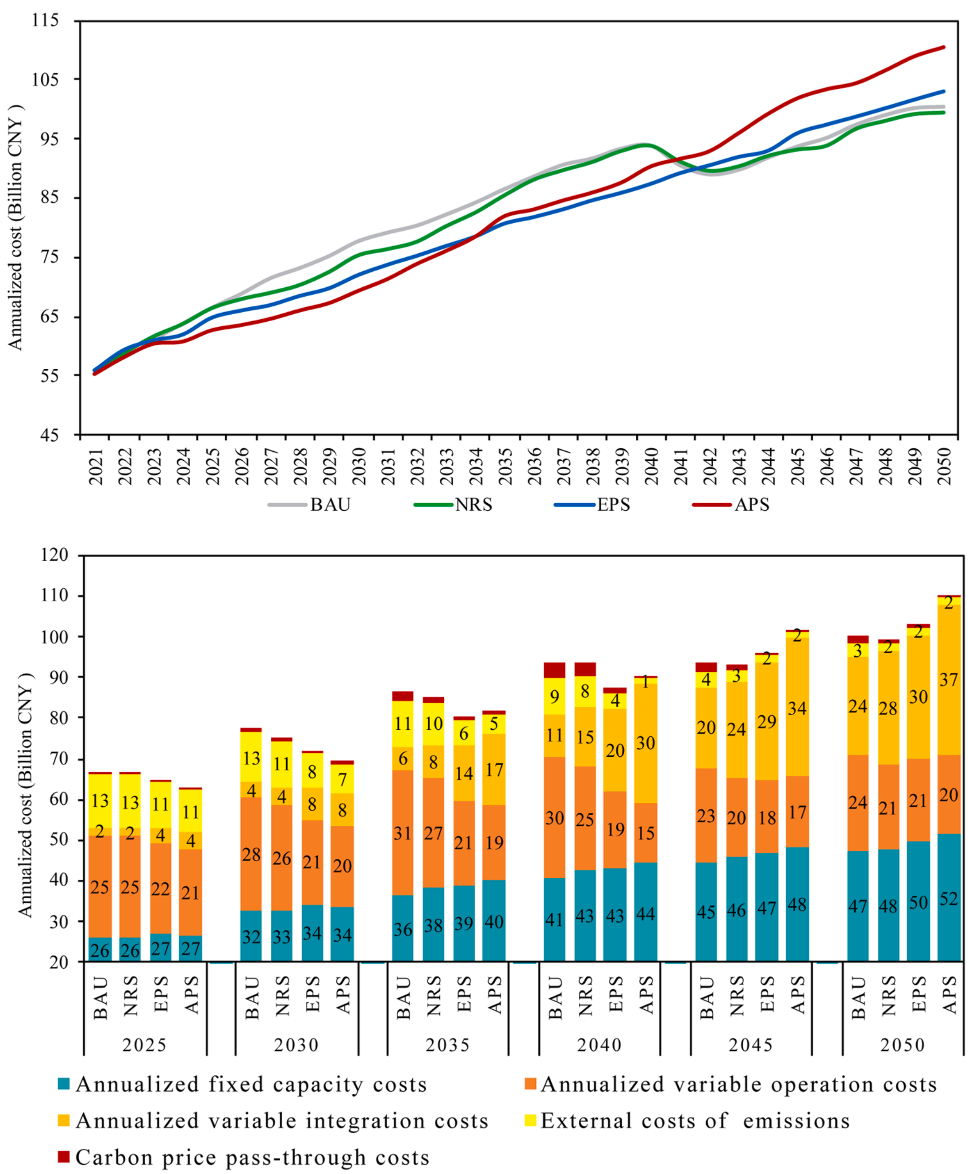

Fig. 11. The annualized generation cost of power plants under different scenarios.

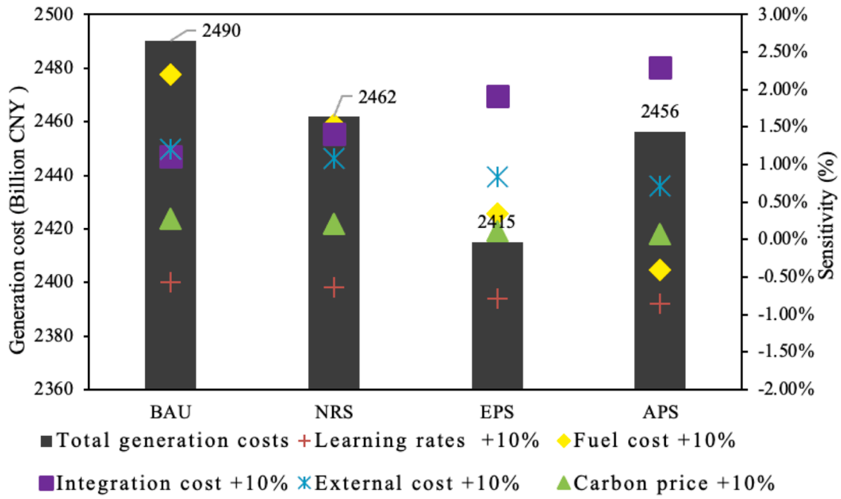

Fig. 12. Total generation costs of power plants from 2021 to 2050.

technologies would require support to integrate into the power system. The high percentage of intermittent renewable power systems brings considerable integration cost uncertainty. Then given the uncertainty of future environmental changes, the external costs from fossil fuel generation emissions can also affect the transition costs. Finally, the carbon price increases and the resulting pass-through costs will also affect the final electricity price.

Fig. 12 presents the sensitivity results in cumulative total generation costs for the power sector, including the learning rate of new energy and battery storage, the fuel cost of coal and gas, integration cost of new energy, the external cost of coal, gas, and biomass power, including carbon price. Setting the sensitivity of these five factors to increase by 10%, the results show that the increase of 10% in fuel cost has a significant impact on the total generation cost for the BAU and NRS scenarios (more than 1.4%), and the increase of 10% in integration cost has a significant impact on the total generation cost for the EPS and APS scenarios (more than 1.9%). In contrast, an increase of 10% in carbon price and learning rate has a smaller impact on the total generation cost (both less than 1%).

Various studies used different appraisal boundaries and methodologies and reported different results. This paper considers the transition costs only in terms of generation costs in the power sector and does not further discuss the interactions between the low carbon transition in the power sector and other sectors of the energy system and the associated costs. Regarding the cost appraisal boundaries, the presented appraisal focuses only on annual system generation costs but does not evaluate investment attractiveness, electricity companies' revenues, short-run or long-run marginal prices, and consumer prices. Such an appraisal extension will become feasible when the pathways are further fleshed out with more detail on hour-by-hour dispatch.

4.3.2. *Comparison of generation costs*

With the introduction of "dual carbon" goals, we should focus more on the affordability of China's ambitious emissions reduction targets, which necessitates an assessment of the electricity costs for the transition. The four pathways have the same power demand level and different power capacity mix scenarios. Therefore, calculated under total generation cost, generation costs per unit are the most suitable indicator for comparing the electricity generation mix costs, as shown in Fig. 13. The results show that the low-carbon power transition could lead to a lower-cost power supply. Compared to the BAU and NRS scenario, under EPS and APS scenarios with higher proportions of new energy sources, the power sector sees a decrease in average generation costs per unit. The average generation costs per unit of electricity for the EPS and APS scenarios are 551 CNY/MWh and 556 CNY/MWh, respectively.

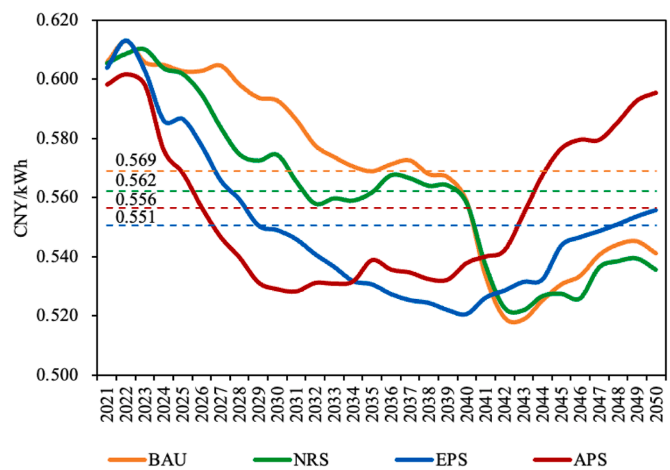

Fig. 13. The generation costs per unit of electricity under different scenarios.

After 2040, compared to the NRS scenario, the average unit cost of electricity generation for the EPS and APS scenarios are 11 CNY/MWh and 40 CNY/MWh higher, respectively. Large-scale new energy sources entering the power system, and increased integration costs carrying the risk of higher electricity prices, may form a barrier to renewable energy investment and lead to high financing costs, which may eventually discourage capital-intensive renewable energy sources for electricity generation projects (Kyritsis et al., 2017). It means that the integration cost of new energy sources should be reasonably cost-sharing to the consumer side, which can positively and effectively contribute to the low-carbon power transition.

4.3.3. *Comparison of transition effectiveness*

With the decline of coal power installed scale, Fig. 14 shows the effect of coal control under different scenarios compared to the BAU scenario. The EPS and APS scenarios would save 168 – 220 million tons of coal and reduce 449 – 614 million tons of CO_2 emissions, significantly better than the NRS scenario. The results show that the earlier phaseout of coal power could significantly reduce black power, coal consumption, and CO_2 emissions.

5. Conclusions and policy implications

First, the simulation results show that Jilin Province could achieve an

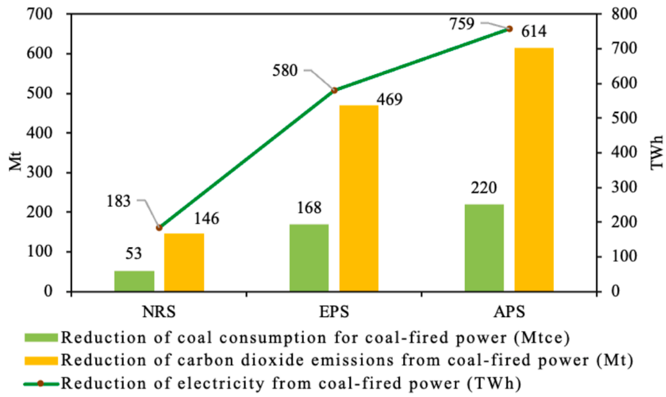

Fig. 14. The transition effectiveness of coal power control under different scenarios.

earlier coal phaseout development scenario under the electric power and energy balance model with abundant resources and reliable power supply, plus large-scale deployment of renewable energy sources and their utilization through energy storage devices. The results also indicate that strictly controlling additional coal power capacity and accelerating renewable energy development during the 14th Five-Year Plan period at the subnational level would help achieve decarbonization.

Second, the results of the cost-effectiveness test to the four scenarios demonstrate that an earlier phaseout of coal power brings possible and affordable transition costs and achieves better coal phaseout effectiveness. The results of the scenarios' assessment also indicate that it is a phased and gradual process to realize clean transition and achieve the "dual carbon" goal. Developing a practical and feasible action plan regarding the cost-effectiveness of the power transition would assist the realization of the process. We suggest that the shareholders in the coal industry optimize the existing coal power units and increase clean energy efficiency (Dong et al., 2018). Meanwhile, it is equally important to accelerate the phaseout of the backward coal power unit.

Last, the research found that achieving a clean and low-carbon transition of the power sector would inevitably increase the integration costs of VRE. The Chinese government should unblock and improve the mechanism of electricity price transmission throughout the supply chain. Historical experiences show that the negative impact of a normal and reasonable increase in electricity prices is much smaller than the huge losses caused by power shortages to the national economy (Ming et al., 2013; Ghaus-Pasha, 2008; Jamil, 2013). Following the principle of "who benefits, who pays" (Verbruggen, 2017), it is necessary to improve the design of the electricity market mechanism. So that the tariff can timely reflect the changes in costs, supply, demand in each section, change the inertia of customers "electricity prices can only go down but not up", and share the cost of the clean energy transition, which should be paid together.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2022.106216.

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