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Optimal pathways toward a carbon-neutral power system considering low-carbon technologies in the Yangtze River Delta region

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A B S T R A C T

Because of its important role in China, many scholars have addressed the decarbonization of the Yangtze River Delta Region (YRDR). However, little work has been conducted on appropriate ways to transform the YRDR power system into a carbon-neutral system. This study develops an optimization model to explore the optimal pathways toward a carbon-neutral power system in the YRDR by 2060. In addition to traditional power generation technologies, the model includes carbon tax (or carbon emission cost), carbon capture and storage (CCS), forest carbon sink (FCS), renewable energy, and energy imports from outside the YRDR. The main findings are as follows: (1) in the business-as-usual (BAU) scenario, the YRDR's power system could reach its carbon peak by 2030, but it would not achieve carbon neutrality by 2060; (2) in the carbon neutrality scenario, FCS could mitigate 88 % of the carbon emissions of the YRDR power system; and (3) a high proportion of renewable energy could help transform the YRDR's power system to a carbon-neutral one, but would increase the cost by 44.8 %. The main policy implication is that implementing a carbon tax and promoting renewable energy, FCS, CCS, and other carbon dioxide removal (CDR) technologies should be considered together to transform the YRDR power system.

1. Introduction

The Yangtze River Delta Region (YRDR) includes Shanghai (SH) municipality, Jiangsu (JS), Zhejiang (ZJ), and Anhui (AH) provinces, and the integration of these areas has been a national strategy of China (Fang et al., 2020). The YRDR is one of China's regions with the most active economies. Despite its relatively limited natural resource endowment (Liu et al., 2020a), the YRDR contributed approximately 24 % of the nation's gross domestic product (GDP) and 20 % of its total electricity consumption in 2020. At the same time, the region was responsible for nearly 19 % of China's total CO_2 emissions (Guan et al., 2021). Thus, achieving carbon neutrality in the YRDR may be more challenging than in other regions of China. The power

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sector accounts for approximately 42.5 % of the YRDR's carbon emissions (Liu et al., 2020b), making it a critical target for mitigation. Finding the optimal pathways toward a carbon-neutral power system for the YRDR is very important for fulfilling China's target of realizing carbon neutrality by 2060 and for its economic development.

Achieving carbon neutrality requires adopting low-carbon technologies such as Carbon Capture and Storage (CCS) and Carbon Dioxide Removal (CDR). CCS refers to the processes that directly capture CO_2 emissions from coal-fired power plants and store them underground to prevent their release into the atmosphere. CDR refers to processes that capture CO_2 from the atmosphere instead of simply reducing its emissions and storing it on land, in the ocean, or as products. Forest carbon sink (FCS) is a conventional method of implementing CDR, which is often known as "negative emissions". These low-carbon technologies have different carbon reduction effects and usually require a large upfront investment and estimation. Therefore, it is important to transition the power system appropriately toward a carbon-neutral system to ensure a safer power supply for the socioeconomic system at the same time.

Many studies have addressed carbon emissions and decarbonization in the YRDR (see the literature review in Section 2). Little work has been conducted to explore the appropriate or optimal pathways for transforming the YRDR power system from a long-term perspective, particularly considering the target of achieving carbon neutrality by 2060. In this study, we developed an optimization model for the YRDR power system based on the MESSAGEix framework from a long-term perspective. Using this model, this study analyzed the optimal pathways toward a carbon-neutral power system in the YRDR from 2020 to 2060, considering different scenarios for implementing a carbon tax and adopting low-carbon technologies, such as FCS and CCS. In this study, the carbon tax can be generalized as the carbon emission cost induced by other policies or mechanisms, such as the cost of buying an emission allowance in the carbon trading market.

The results of this study could provide suggestions on how the YRDR should transition its power system toward a carbon-neutral system. The model framework developed in this study can be easily adapted to analyze the transition of energy systems in other regions. The remainder of this paper is organized as follows. Section 2 reviews the relevant literature. Section 3 introduces the methodology and data used in the study. Section 4 presents the optimal pathways for transitioning the YRDR power system under different scenarios. Section 5 discusses the implications of these results. Finally, Section 6 provides concluding remarks.

2. Literature review

An increasing number of scholars are focusing on carbon emissions in the YRDR. For example, Gao (2022) predicted that the carbon emissions of the YRDR from 2020 to 2035 would be between 2041 and 2308 million tons (Mt), and Wu et al. (2021) projected that the carbon emissions of the YRDR would reach 2935 Mt by 2050. Scholars have argued that, as the largest metropolitan area in China (She et al., 2021), the YRDR's urbanization has a negative impact on carbon reduction, and provincial governments in the YRDR should coordinate with each other to reduce carbon emissions (Li et al., 2018b). Liu et al. (2021b) implied that the YRDR's carbon reduction should not be determined by economic or environmental policy alone. Moreover, Chen et al. (2022) proposed that the risk level of energy security for the YRDR will continue to increase from 2006 to 2025.

An increasing number of scholars have addressed the decarbonization of the YRDR, particularly its power system. For example, Wu et al. (2021) proposed that the YRDR could achieve the goal of a 60 %–65 % carbon reduction per GDP from 2005 to 2030, and Peng et al. (2022) proposed that the establishment of distributed solar photovoltaic (PV) plants should be encouraged for the decarbonization of the YRDR. Zhang et al. (2024) modeled a full year of power system operations, sub-provincial renewable energy siting criteria, and transmission connections. They found that distributed solar power becomes economically feasible in the YRDR under high demand, where utility-scale deployment is limited by competition with agricultural land. Li et al. (2018a) analyzed the transfer of the YRDR's carbon emissions to other areas associated with interprovincial electricity transmission and found that direct electricity purchased from outside the YRDR could promote the development of the YRDR's renewable energy but would result in a higher cost for the YRDR. These studies highlighted the urgency of transforming the YRDR's energy structure into a low-carbon system but rarely explored the appropriate or optimal pathways for transforming the YRDR power system from a long-term perspective, especially considering the goal of reaching carbon neutrality by 2060.

Scholars have argued that carbon tax could be an effective policy for carbon reduction (Ghazouani et al., 2020; Liu et al., 2021a), which could induce the earlier adoption of low-carbon technologies (Ding et al., 2019; van Den Bergh and Botzen, 2020). Scholars have also explored the combination of a carbon tax with subsidies for low-carbon or CDR technologies and found that it would be more effective than implementing a carbon tax alone (Fan and Friedmann, 2021; Zhang et al., 2017b). As mentioned previously, the carbon tax in this study can be generalized as the carbon emission cost induced by other policies or mechanisms, such as the cost of buying an emission allowance in the carbon trading market.

FCS and CCS are the most widely used low-carbon technologies (Buck et al., 2020; Ge et al., 2023; Hao et al., 2022; Tanzer et al., 2020; Tian et al., 2022). The Paris Agreement has highlighted FCS as a potential carbon sink to reduce carbon emissions, and projections suggest that China's forest biomass carbon stock could increase by more than 50 % by 2050 (Ge et al., 2023). In recent years, researchers have studied the impact of forest carbon sinks on carbon neutrality (Chen et al., 2021; Xu et al., 2023; Zhao et al., 2023). Ray and Jana (2017) calculated that approximately 4328 km^2 of mangrove forest coverage was required to mitigate all the CO_2 emitted from the Kolaghat power plant. Liu et al. (2022) found that the cost of afforestation to reduce carbon emissions is lower than that of adopting renewable energy. CCS enables the upgrading of existing coal-fired power plants to low-carbon ones while maintaining coal for power generation (Hammond and Spargo, 2014). Retrofitting traditional power plants with CCS can reduce the demand for new large-scale power plants (Abdilahi et al., 2018).

Compared with existing studies, this study's main innovation is the development of a long-term system optimization model with a carbon tax and two types of low-carbon technologies (FCS and CCS) to analyze the low-carbon development pathways of the YRDR power system considering carbon neutrality by 2060.

3. Methodology and data

3.1. The YRDR's power system model

This study established a long-term power system model for the YRDR based on the Model for Energy Supply Strategy Alternatives and their General Environmental Impacts (MESSAGE). This model is a bottom-up optimization model widely used to analyze energy systems and provide core inputs for major international assessments, such as the Intergovernmental Panel on Climate Change (IPCC), World Energy Council (WEC), and Global Energy Assessment (GEA) (Esmail and Cheong, 2021; Grubler et al., 2018; Guo et al., 2022; Jie et al., 2021; Zhang et al., 2018, 2019). MESSAGEix is a platform developed by the International Institute for Applied System Analysis (IIASA) that improves the openness and transparency of MESSAGE models and provides an efficient workflow for data processing and model implementation (Huppmann et al., 2019). Moreover, MESSAGEix allows the modeling of all steps in the energy flow from supply to demand, which is generally referred to as the energy chain, and the steps are called levels.

Based on the MESSAGEix platform, the YRDR's power system is structured into energy flows, including the resource level (coal, oil, gas, biomass, etc.), primary energy level (coal, oil, gas, etc.), secondary energy level (electricity), and demand level (electricity) for each sub-region (Shanghai, Jiangsu, Zhejiang, and Anhui) in the YRDR. As shown in Fig. 1, these levels are linked by different technologies, such as resource extraction and power generation technologies, etc. Energy flows between the YRDR sub-regions and between the YRDR and other regions in China are connected by resource or electricity transportation and distribution (T&D).

The underlying principle of MESSAGEix is to optimize an objective function under a set of constraints that define the feasible region containing all possible solutions to the problem. By default, MESSAGEix minimizes the accumulative total system costs as a criterion for optimization (Messner et al., 1996). It can search for the optimal mix of energy technologies that satisfy the given constraints while minimizing costs.

In the YRDR power system model, the total cost is composed of four parts: investment, operation and maintenance (O&M), fuel, and carbon emissions. The main data inputs for MESSAGEix include the time horizon, discount rate, power plant

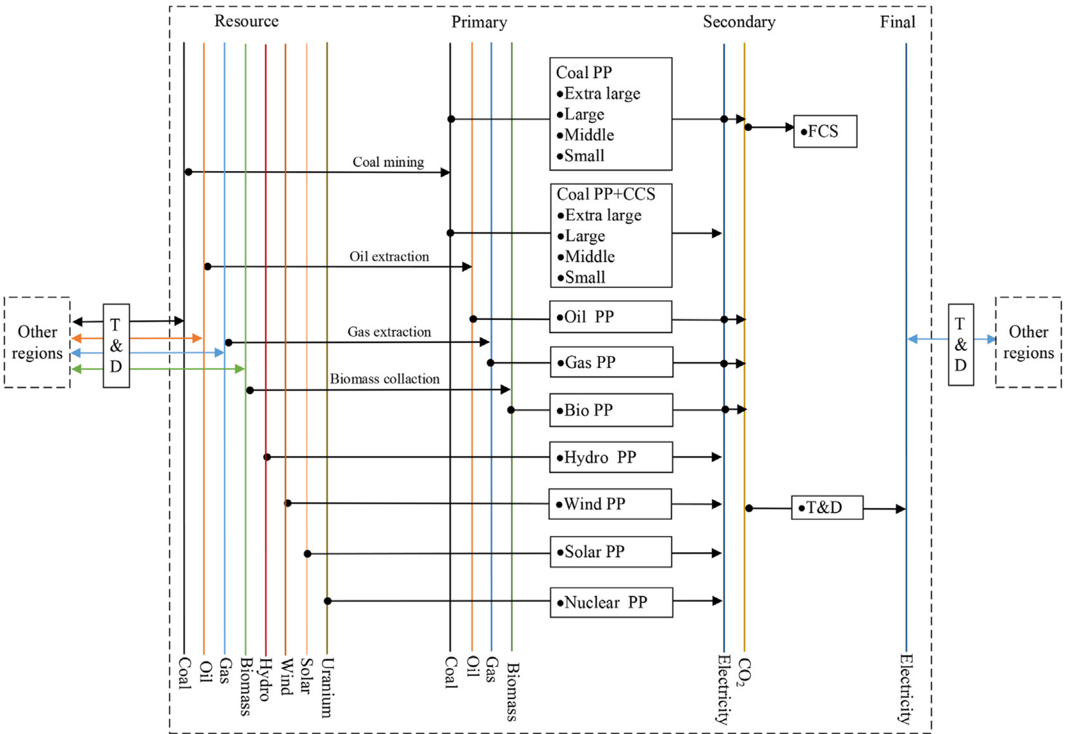

Fig. 1. Simplified energy system flow diagram in each sub-region of the YRDR power system.

efficiency, historical installed capacity, capacity factors, initial investment cost, O&M cost, electricity demand, emission factor, and lower or upper limits for each technology. MESSAGEix determines how available technologies are used to satisfy each sub-regional demand. The system's optimal solutions include technology activities, capacity, and carbon emissions. This study sets the discount rate to 3 %, following Jie et al. (2021) and Wiser and Millstein (2020).

3.2. Resource level

As shown in Fig. 1, the resource level refers to natural resources, including non-renewable and renewable natural resources. Non-renewable resources include coal, oil, and gas in the ground and biomass in the field. Non-renewable resources account for a relatively high proportion of the resource consumption in the YRDR. Owing to the geographical location and resource endowment of the YRDR, the reserves of non-renewable resources such as coal, oil, and gas are very poor. Coal resources in the YRDR depend mainly on imports from other provinces of China, oil resources depend on imports from other countries and natural gas resources are considered. The volume of the resource (coal, oil, gas, and bio) supply in the YRDR was set according to the guidelines of the National Bureau of Statistics of China (NBSC, 2020), as shown in Table 1.

The YRDR falls into category IV wind energy resources and category III solar energy resources (Weng et al., 2021). Based on previous studies on China's provincial-scale solar, wind, and hydropower resource potential (He and Kammen, 2016; Li et al., 2018c; Qi et al., 2022b; Qiu et al., 2022; Sun et al., 2019; Wang et al., 2022; Yang et al., 2019; Zhang et al., 2024) as well as the projections of the State Grid Energy Research Institute (SGERI, 2020), the assumed upper limits for the capacities of different renewable energy technologies in the YRDR in each period are shown in Table 2. The detailed constraints for each sub-region are shown in the Supplementary Data.

3.3. Primary level

The primary level involves the raw product at a generation site, such as coal preparation, which is considered an essential way to promote the clean and efficient utilization of coal. Therefore, the primary energy sources are coal, extracted oil, extracted gas, and collected biomass. The resource prices of each sub-region in the YRDR were obtained from the CEIC database (ceicdata.com) and the CCTD coal information portal (cctdcoal.com), as shown in Table 3.

3.4. Secondary level

The secondary level includes other forms of energy (e.g., electricity) obtained by processing and converting the primary energy. Coal is the largest source of electricity in the YRDR, with nearly 82 % share. Efficiency and O&M costs (including variable and fixed costs) differ for coal-fired plants of different sizes. Coal-fired power plants (PP) in our model are classified into four groups according to their scale, namely, small (PPS, ≤ 300 MW), medium (PPM, 301–600 MW), large (PPL, 601–999 MW), and extra-large (PPXL, ≥ 1000 MW). Their efficiencies and O&M costs were estimated according to the CEC

Table 1
Non-renewable resources supply in the YRDR in 2019 (unit: GWa).

Resource supply	Anhui	Jiangsu	Shanghai	Zhejiang
Coal	72.86	7.31	0.00	0.00
Oil	1.79	25.87	0.00	0.00
Gas	0.03	2.41	0.00	0.00
Biomass	27.44	23.98	1.12	10.54

Table 2
Upper limits for capacities of renewable energy technologies in the YRDR (unit: GW).

Technology	2025	2030	2035	2040	2045	2050	2055	2060
Hydro	23.75	28.44	32.84	36.83	40.82	44.80	48.41	52.04
Wind	43.66	64.83	86.40	107.97	129.55	151.12	172.69	194.26
Solar	106	194	281	369	457	545	633	721

Table 3
The price of raw products in the YRDR in 2019 (unit: MUSD/GWa).

Primary energy price	Anhui	Jiangsu	Shanghai	Zhejiang
Coal	143.31	132.75	129.66	142.91
Oil	11.16	11.16	11.16	11.16
Gas	453.55	453.55	453.55	453.55
Biomass	0.21	0.21	0.21	0.21

(2020) and Yi et al. (2016). The investment costs were estimated by Chang et al. (2017) and Zhang et al. (2018). The capacity factors were obtained from the China Electric Power Yearbook (CEP, 2020). The carbon emissions factor was obtained from Zhang et al. (2018). We explicitly model CCS technology as a separate technology, classified as "addon" technology in the MESSAGEix platform, which is linked to the activity of the coal-fired power plant technology it serves. The initial investment cost and O&M costs of the CCS technology were estimated based on Chen et al. (2021).

The model also includes four clean power generation technologies: hydro, wind, nuclear, and solar. Following the traditional method of dealing with clean energy (Zhang et al., 2016, 2017a, 2021), their efficiencies and carbon emission factors were treated as 100 % and 0 Mt/Gwa, respectively. The requirements of the new power plant capacity are based on the historical capacities and their lifetimes. The historical capacities of the power plants were obtained from previous studies (Cai et al., 2016; Chen et al., 2021; SGERI, 2020; Shan et al., 2015), whereas their lifetimes were obtained from Chen et al. (2021) and Zhang et al. (2012), as shown in Table 4.

Coal-fired power plants without CCS can convert primary energy (primary level) into electricity and carbon emissions (secondary level). FCS, as a "virtual technology" for carbon dioxide absorption within the system, can mitigate CO_2 from the atmosphere. The FCS costs for each sub-region in the YRDR were derived by Zhou et al. (2019) and Qin et al. (2017). The FCS scale can be estimated based on the forest areas and their carbon absorption capacity in the sub-regions of the YRDR. The carbon emissions from the power sector contribute 42.5 % of the total carbon emissions of the YRDR (Liu et al., 2020b). Therefore, in the model, we assumed 42.5 % of the forest area for each sub-region as the upper limit for the FCS. Additionally, this assumption does not exclude other assumptions about how much the power sector uses FCS to mitigate CO_2 emissions. It is just used for setting the scenarios in this study. Therefore, we also conducted a sub-scenario in which all the current YRDR forests are used to mitigate the CO_2 emissions from the YRDR's power system, as well as a sub-scenario in which no FCS is used in S-III-2. The carbon absorption capacity is about 40t CO_2 $ha^{-1}year^{-1}$(Bernal et al., 2018). The supplementary data provide more detailed technological parameters and data for these technologies.

3.5. Final level

The final level is the final product satisfying the regional demand, such as electricity from renewable or non-renewable resources. The final electricity demand is calculated based on historical data (NBSC, 2020) and projections from the State Grid Energy Research Institute (SGERI, 2020). Using the power demand growth rate in the SGERI projection, we generated a projection of the YRDR's electricity demand from 2020 to 2060, as shown in Table 5.

3.6. Energy transportation and distribution

As mentioned before, the model includes the energy flows between the YRDR sub-regions as well as the energy flows between the YRDR and other regions in China, including fossil fuel T&D and electricity T&D. Existing railway facilities for fossil fuel T&D are well developed in the YRDR. Therefore, we do not consider investment costs; only O&M costs are related to distance. The railway line distance was obtained from HUOCHEPIAO (2016), and the O&M costs of the railways were

Table 4
Parameters of the power generation technologies.

Technology	Efficiency (%)	Variable cost (MUSD/GWa)	Fixed cost (MUSD/GW/a)	Plant life (year)	Emission factor (Mt/GWa)
Extra-large	45	49.91	21.65	30	6.87
Large	41.5	39.92	19.05	30	6.94
Middle	39.5	39.92	17.25	30	7.57
Small	35	39.92	19.04	30	7.72
Bio	41	69.02	63.49	30	7.57
Oil	39	27.81	17.91	30	7.10
Gas	45	132.62	58.28	30	3.38
Hydro	100	0	17.09	70	0
Wind	100	0	17.59	20	0
Nuclear	100	0.04	97.68	60	0
Solar	100	0	3.97	25	0

Table 5
The sub-regional power demand in the YRDR (unit: GWa).

Sub-region	2020	2025	2030	2035	2040	2045	2050	2055	2060
Anhui	28	34	41	43	45	46	46	48	49
Jiangsu	73	89	107	113	118	121	122	126	129
Shanghai	18	22	27	28	29	30	30	31	32
Zhejiang	55	67	81	86	89	92	92	95	98

calculated based on Yi et al. (2016), as listed in Table 6. The loss of fossil fuels during railway transportation was 1.2 % (Yu et al., 2014).

Most electricity in the YRDR is imported from other regions, such as southwest China. China has been building ultrahigh-voltage (UHV) lines as a long-distance power transmission backbone network. Six UHV lines connected to the YRDR were constructed by 2020; their detailed parameters are listed in Table 7. The investment and O&M costs of UHV transmission lines are related to the distance between two provinces. These values were calculated by referring to Guo et al. (2022), Chen et al. (2021) and Yi et al. (2016). The UHV transmission loss was approximately 0.004 % per kilometer (Ding and Hu, 2006; Zhang et al., 2018). The efficiencies of the UHV transmission lines between regions are also listed in Table 7.

3.7. Scenario assumptions

In this study, three scenarios were constructed: business-as-usual (BAU) scenario (Scenario I), carbon reduction scenario (Scenario II), and carbon neutrality scenario (Scenario III).

Scenario I (S-I) follows the reference scenario 2050 outlined in the China Energy and Electricity Outlook 2020 (SGERI, 2020) and extends it to 2060, which does not explicitly consider carbon reduction policies and low-carbon technologies.

Scenario II (S-II) assumes the implementation of a carbon tax and the adoption of low-carbon technologies to reduce carbon emissions based on the BAU scenario. The actual carbon price levels remain highly uncertain, especially in the distant future. According to the 2020 China Carbon Pricing Survey (Slater et al., 2020) and studies by Jie et al. (2021) and Ding et al. (2019), the carbon tax is estimated to be 49 yuan/t CO_2 with an annual growth rate of 5 %. FCS and CCS were incorporated into the model as low-carbon technologies. To explore the effects of the carbon tax, FCS, and CCS, Scenario II is further set with sub-scenarios indicating whether these elements are included, as shown in Table 8.

Scenario III (S-III) sets the constraint that the YRDR's power system will achieve carbon neutrality by 2060 based on S-II-1. China has vigorously promoted the development of renewable energy as an important part of achieving carbon neutrality, and its energy system is expected to increase the proportion of renewable energy (Bai et al., 2020; Impram et al., 2020; Liu et al., 2021c). The YRDR government also announced the development of renewable energy (Chen and Lin, 2021; Gao and Pan, 2022; Xie et al., 2021). To explore how the carbon neutrality target and high proportion of renewable energy influence the transition of the YRDR's power system, we set the following sub-scenarios for Scenario III: S-III-1 and S-III-2.

- S-III-1. In S-III-1, which is based on S-II-1 with a carbon tax, the constraint that the YRDR's power system will be carbon-neutral by 2060 is added.

Table 6
O&M costs of fossil fuel transportation (unit: MUSD/GWa).

Sub-region	Anhui	Jiangsu	Shanghai	Zhejiang
Anhui	–	3.65	4.41	4.00
Jiangsu	3.65	–	3.62	3.94
Shanghai	4.41	3.36	–	3.62
Zhejiang	4.00	3.94	3.36	–

Table 7
Parameters for existing UHV transmission lines by 2020.

UHV line	O&M (MUSD/GWa)	Investment (MUSD/GWa)	Efficiency (%)	Linked sub-region
Jinbei-Nanjing	9.89	329.65	96.70	Shanxi-Jiangsu
Jinping-Jiangsu	14.92	497.42	93.82	Sichuan-Jiangsu
Ningdong-Zhejiang	14.47	482.27	94.84	Ningxia-Zhejiang
Xiangjiaba-Shanghai	17.76	592.00	94.28	Yunnan-Shanghai
Xiluodu-Zhejiang	14.56	485.43	95.04	Yunnan-Zhejiang
Ximeng-Taizhou	12.40	413.49	95.14	Inner Mongolia-Jiangsu

Table 8
Three sub-scenarios of Scenario II.

Sub-scenarios	Whether included or not		
	Carbon tax	FCS	CCS
S-II-1	✓	✓	✓
S-II-2	✓	–	–
S-II-3	✓	✓	–

- S-III-2. S-III-2 is based on S-III-1, with the additional constraint that the share of renewable energy power generation in the YRDR's power generation will be at least 36 %, 50 %, 60 %, 70 %, 75 %, 82 %, 85 %, and 88 % from 2025 to 2060 with 5-year intervals while being subjected to the upper limit constraints in Table 2.

The relationship of all six scenarios is illustrated in Fig. 2.

4. Results

4.1. The transition of the YRDR's power system in the BAU scenario

Fig. 3 shows the carbon emissions of the power system during the YRDR peak in 2030 under the BAU scenario. Carbon emissions are expected to decrease gradually from 920.8 Mt in 2030 to 742 Mt in 2060. This trend is consistent with the conclusions of Gao (2022). Notably, the Shanghai government aimed to peak Shanghai's carbon emissions by 2025 (Gao and Pan, 2022). The results of our BAU scenario imply that Shanghai has to adopt more stringent carbon reduction measures.

The future electricity demand is crucial for transforming the power sector toward a carbon-neutral system. We run the model using a high-demand electricity scenario (see Fig. 4(a)) based on the 2021 forecast by the Global Energy Interconnection Development and Cooperation Organization (GEIDCO, 2021) and a low-demand electricity scenario (see Fig. 4(b)) derived from the 2022 report by the International Energy Agency (IEA, 2022). Not surprisingly, CO_2 emissions increase with rising electricity demand.

4.2. The transition of the YRDR's power system in scenario II

Implementing carbon taxes and adopting low-carbon technologies are believed to play important roles in transiting energy systems. Using the three sub-scenarios in S-II, we explore how the carbon tax, FCS, and CCS influence the transition of the YRDR power system.

In Scenario S-II-1, in which the carbon tax is implemented and both FCS and CCS are available for adoption, the power generation structure is very similar to that in the BAU scenario (see Fig. A1 in Appendix A). However, the carbon emissions decrease significantly compared with S-I. Fig. 5 shows that the total carbon emissions in S-II-1 are approximately 458 Mt in 2060, achieving a 38.2 % reduction. Although S-II-1 includes a carbon tax, FCS, and CCS technology without mandatory policy requirements, the YRDR power system may still fail to achieve carbon neutrality by 2060.

Regarding the installed power generation capacity, S-II-1 is similar to S-I (see Fig. B1 in Appendix B). Although the carbon tax in S-II-1 would encourage the adoption of larger-scale renewable energies such as hydropower, wind, and utility-scale solar power plants, these power plants are constrained by the YRDR's low resource endowment and limited land (Zhang et al., 2024). The biggest difference in S-II-1 is an obvious increase in new CCS and FCS capacity. Fig. 6 shows the details of the different types of coal-fired power plants that will be newly equipped with CCS for the sub-regions in the YRDR during various periods. Around 36.62 GW (nearly 20 %) coal-fired power plants will be equipped with CCS in 2060, contributing to 107.72 Mt (nearly 30 %) carbon emission reduction of the YRDR's power system.

Fig. 7 shows that the CO_2 emissions from the power system could be mitigated by FCS in the YRDR sub-regions. From this, we can see that the FCS used for absorbing carbon emissions will gradually increase and will absorb nearly 40 % of the power system's carbon emissions by 2060. For each sub-region, the FCS will absorb 65 %, 56 %, 15 %, and 3 % of the power system's carbon emissions in Zhejiang, Anhui, Jiangsu, and Shanghai, respectively.

A carbon tax is thought to drive the adoption of low-carbon technologies. Still, the future carbon tax (or carbon emission cost in general) is difficult to predict, as it is influenced by the complex external environment, such as energy demand, regional economy, and policies (Qi et al., 2022a). We conducted a sensitivity analysis on the carbon tax in S-II. Fig. 8 shows the total cost and carbon emissions of the YRDR's power system with different carbon tax growth rates in sub-scenarios S-II-1, S-II-2, and S-II-3.

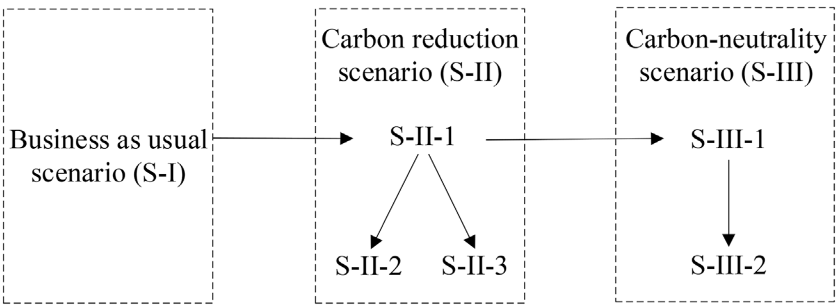

Fig. 2. The relationship between the six scenarios.

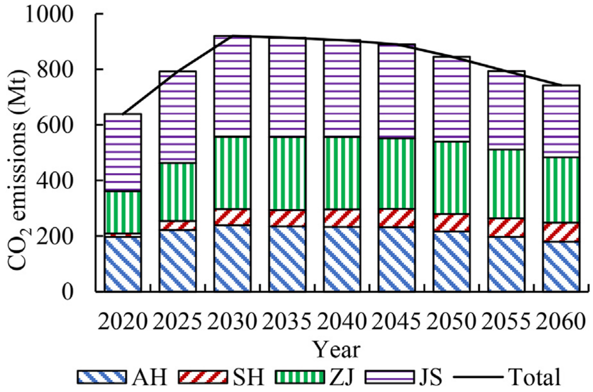

Fig. 3. CO_2 emissions of the YRDR power system under the BAU scenario.

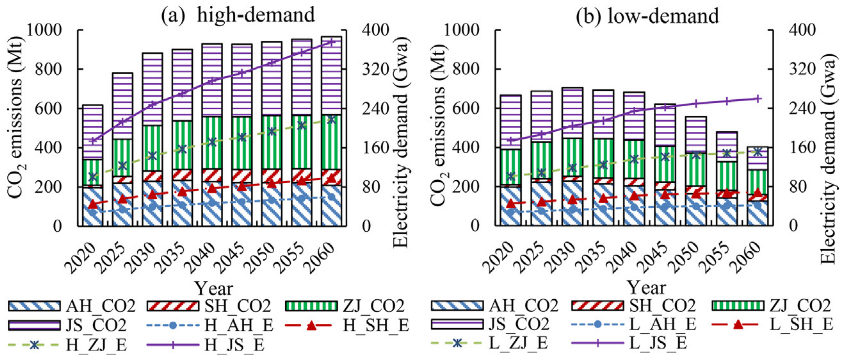

Fig. 4. CO_2 emissions from the YRDR power system with different electricity demands.

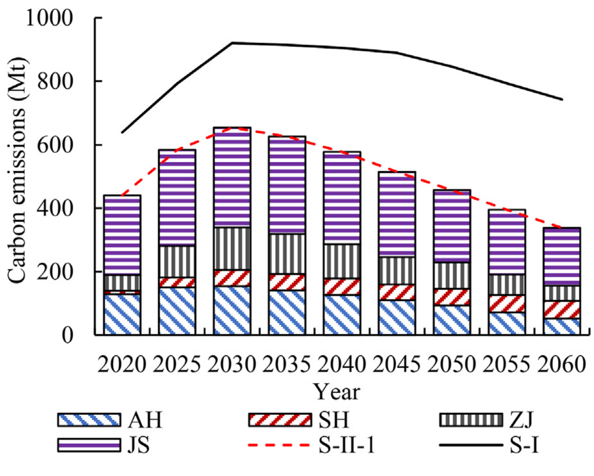

Fig. 5. CO_2 emissions of the YRDR power system under S-II-1.

In Fig. 8(a), the total system cost will gradually increase as the carbon tax rises, especially for S-II-2, which will be much higher than those of S-II-3 and S-II-1. The gap will increase as the carbon tax rises. In Fig. 8(b), if both the FCS and CCS are not available, which is the case for S-II-2, the implementation of a carbon tax can not reduce the volume of carbon emissions significantly until the growth rate of the carbon tax increases to 9 %. This result implies that combining a carbon tax with low-carbon technologies is more effective than implementing a carbon tax alone, which also confirms the findings of the studies of Liu et al. (2021b) and Fan and Friedmann (2021).

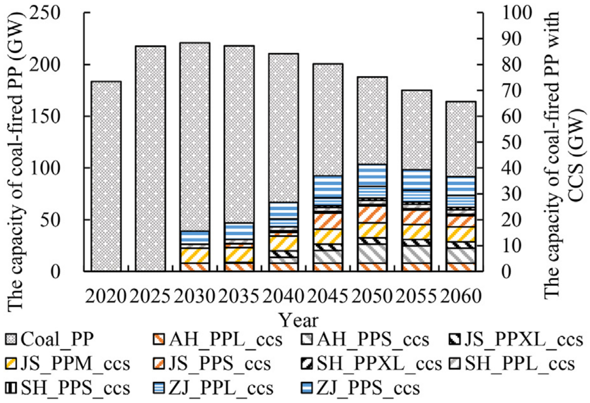

Fig. 6. The capacity of coal-fired power plants with CCS.

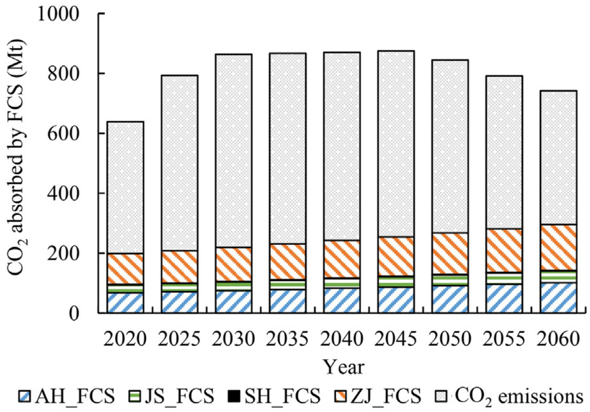

Fig. 7. CO_2 emissions mitigated by FCS in the YRDR power system.

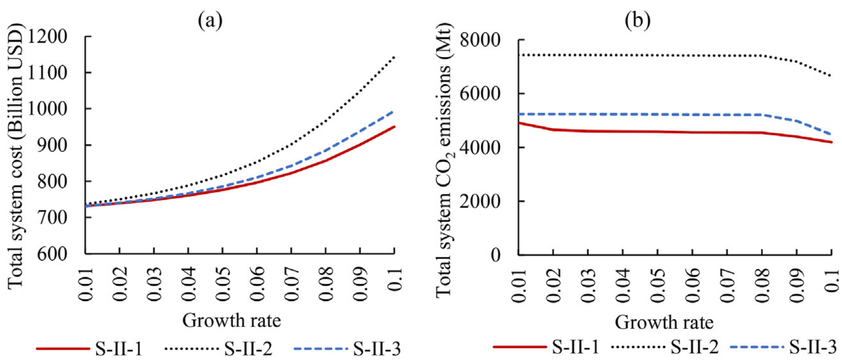

Fig. 8. Total system cost and carbon emissions for the different carbon tax.

By comparing S-II-2 and S-II-3, we observed that after integrating the FCS into the system, the total system CO_2 emissions decreased from over 7400 Mt to approximately 5200 Mt, representing a significant reduction of approximately 30 %. This demonstrates the crucial role of the FCS in reducing carbon emissions in the YRDR power system. Comparing S-II-3 with S-II-1, we find that the total system cost of S-II-3 is higher than that of S-II-1, and the overall system carbon emissions of S-II-3 approach those of S-II-1 when the carbon tax growth rate reaches 10 %. This outcome implies that the adoption of CCS reduces carbon emissions and decreases the total system cost.

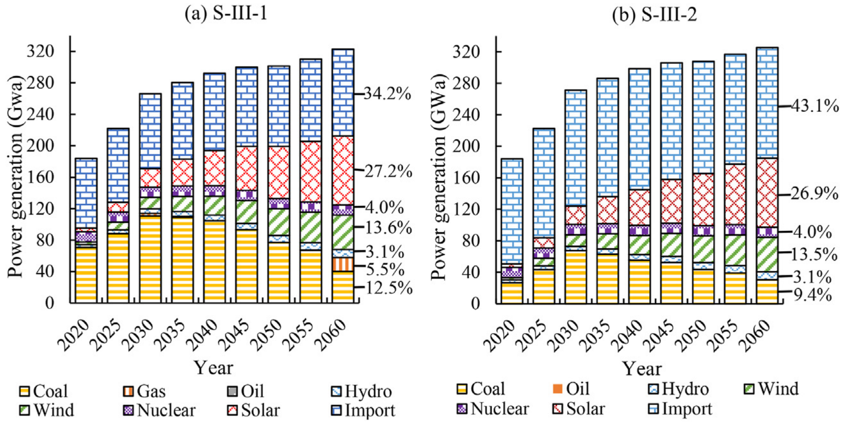

Fig. 9. The power generation structure of S-III-1 and S-III-2.

4.3. The transition of the YRDR's power system in scenario III

Fig. 9(a) shows the power generation mix in the YRDR under the carbon neutrality scenario S-III-1, which includes the constraint that the YRDR's power system will be carbon-neutral by 2060 based on S-II-1. The proportion of gas-fired power generation will dramatically increase to 5.5 % because gas-fired power generation has lower carbon emissions and higher efficiency compared to coal-fired power plants. However, resource scarcity (Table 1) limits the development of gas-fired power plants. In addition, electricity imported from provinces outside the YRDR will increase by 34.2 % by 2060 (approximately 15.2 % in S-I, see Fig. A1).

Fig. 9(b) shows the power generation structure of S-III-2. After adding low-limit constraints to the proportion of renewable energy, coal-fired power generation is expected to drop to 9.4 % by 2060. In contrast, power imported from provinces outside the YRDR will significantly increase, reaching 43.1 % in S-III-2. This result implies that a strategy of developing a high proportion of renewable energy can promote carbon neutrality but leads to excessive pressure on power imports from provinces outside the YRDR, which also confirms the conclusion of Li et al. (2018a).

Fig. 10 shows the carbon emissions of the YDRD's power system in S-III-1 and S-III-2. Under both scenarios, the YRDR's power system could achieve carbon neutrality by 2060. The total system CO_2 emissions from 2020 to 2060 in S-III-2 will be reduced by approximately 60 % compared with S-III-1. Specifically, Zhejiang will take the lead in achieving carbon neutrality, and Shanghai will achieve carbon neutrality by 2050.

As mentioned before, we assumed that 42.5 % of the forest area for each sub-region was the upper limit for the FCS. Fig. 11(a) presents the volume of carbon reduction for the two low-carbon technologies (FCS and CCS) in S-III-2, which indicates that most of the carbon emissions would be generated by coal-fired power technologies and eliminated by FCS by 47 % in 2030 and by 88 % in 2060. It is difficult to predict how much FCS is used to mitigate CO_2 emissions in the YRDR's power sector. We also conducted a sub-scenario in which all the current YRDR forests are assumed to mitigate the CO_2 emissions from the YRDR's power system, as shown in Fig. 11(b). In this sub-scenario, FCS will contribute to nearly 95 % CO_2 reduction in 2060. We also set a sub-scenario in which FCS is not used at all in S-III-2, and the results show that the model could not find an optimal solution. This outcome implies that the YRDR's power system needs to mitigate its emissions through other ways, such as purchasing carbon emission rights from projects of Chinese Certified Emission Reduction (CCER).

The reason for the high proportion of FCS is that the cost of using FCS is nearly half that of CCS technology, which is considered another low-carbon technology. The system model built in this study aims to minimize costs, leading to a preference for lower-cost technologies. Additionally, with a future increase in the proportion of renewable energy generation in S-III-2, the share of coal-fired power generation will decline, thereby limiting the opportunities for CCS retrofitting.

Fig. 12 shows the power imports from provinces outside the YRDR and the total system costs under different scenarios. Fig. 12(a) shows that the electricity imports in S-III-2 are higher than those in the other scenarios, which means that to achieve carbon neutrality with a high share of renewable energy, a large amount of electricity must be imported from other regions, such as southwest China. From Fig. 12(b), we can see that electricity imports from other provinces outside the YRDR would make the entire YRDR's power system much more costly, 44.8 % higher than the total cost in the BAU scenario. This projected result is consistent with the conclusion of Li et al. (2018a).

5. Discussion

The results show that the future carbon emissions of the YRDR power system will maintain a growing momentum until 2030 and achieve its carbon peak in 2030. Although renewable energy generation plays an important role in the YRDR power

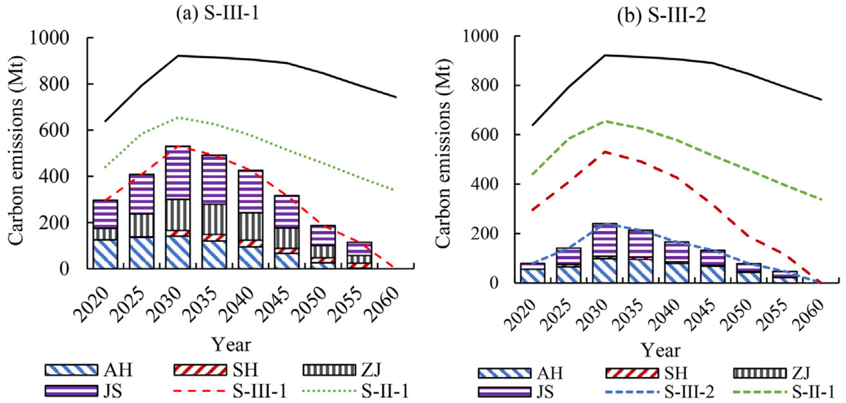

Fig. 10. CO_2 emissions of the YRDR's power system in S-III-1 and S-III-2.

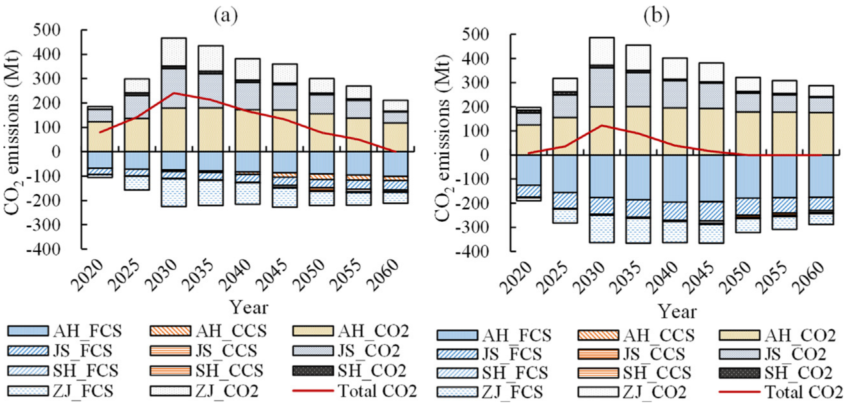

Fig. 11. The volume of carbon reduction for the different forest coverages in S-III-2.

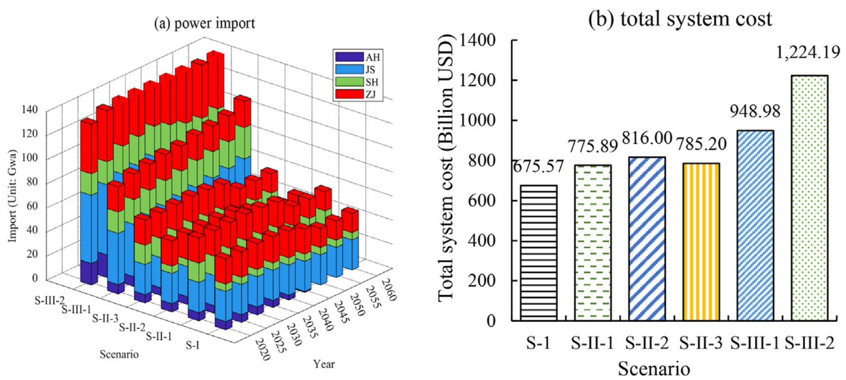

Fig. 12. Power imports and total system cost in the different scenarios.

system, the power system will not be able to achieve carbon neutrality by 2060 if measures are not taken, such as implementing carbon tax policies and adopting low-carbon technologies. The main reason for limiting the development of large-scale renewable energy power plants is land availability in the YRDR. Its high population density (230 million of the total population, only 358,000 square kilometers) makes potential suitable new sites for large-scale renewable energy power plants unlikely to compete with human use. Similarly, there was no further increase in nuclear power owing to a lack of suitable locations.

Although the further development of large-scale renewable energy is restricted in the YRDR, this does not mean that there is nothing to do. In contrast, as one of the most developed regions in China's industrial economy, the YRDR has an early deployment of low-carbon technological innovation and transformation, upgrading of energy equipment, and industrial agglomeration. The YRDR can further leverage these advantages to develop renewable energy according to the conditions of the sub-region. For example, in the BAU scenario, Anhui could invest more in distributed solar power to increase its capacity. Jiangsu can increase its offshore wind power capacity investments. Shanghai could build additional UHV transmission lines to increase its transmission capacity. In addition to increasing the amount of distributed solar power, Zhejiang can fully utilize its nuclear and wind power. In the future, with breakthroughs in new energy technologies, such as biomass and tidal energy, there will still be more room for improvement in the development of renewable energy in the YRDR.

Our research found that if only carbon tax policy was implemented without technological innovation, the impact of the carbon tax on carbon reduction in the YRDR would not be significant and would increase the additional system cost. Achieving a carbon tax is important in promoting the long-term adoption of low-carbon technologies. The FCS is important in removing CO_2 emissions and can contribute to about 88 % carbon reduction by 2060 in the carbon neutrality scenario. Expanding forest areas will be economically feasible and low-cost in the coming decades. Moreover, FCS cannot immediately remove carbon from a short-term perspective because forests require time to grow.

Another key to carbon reduction is retrofitting coal-fired power plants using CCS. Given the dominance of coal in China, most electricity from coal could have lower CO_2 emissions owing to the widespread adoption of CCS technology. In the carbon neutrality scenario, the results show that the amount of CO_2 captured through CCS will account for approximately 12 % of the CO_2 emissions from the YRDR power system. One of the main barriers to adopting CCS technology is cost. For instance, the investment of CCS is twice as high as that of a coal-fired power plant with extra-large capacity. However, CCS should contribute to significant cost reductions through learning-by-doing and economies of scale. China's largest CCS pilot project with an annual capacity of 150,000 tons, the Guohua power Jinjie power plant, has been put into trial operation. Therefore, there is an urgent need to formulate relevant policies that enable large-scale commercial deployment. Another way to promote the development of CCS technology is to impose a high tax on CO_2 emissions. A high carbon tax and energy consumption will drive enormous investment in CCS technology to achieve significant overall CO_2 emissions reduction.

In the carbon neutrality scenario, zero carbon emissions could shift power generation from coal to natural gas. However, Table 1 shows that the YRDR does not have abundant natural gas resources; therefore, increasing the installed capacity of natural gas may have little effect on carbon reduction in the short term. We also found that a high share of renewables might not be economically optimal from a CO_2 reduction perspective as it would lead to direct electricity purchases from other regions, such as southwest China. However, other policy goals, such as improving industrial structure and regional sustainable development, can be achieved through the extensive use of renewable energy.

6. Conclusion and policy implications

This study developed an optimization model for the YRDR power system based on the MESSAGEix framework from a long-term perspective, mainly focusing on analyzing the optimal strategies for low-carbon development pathways of the YRDR power system at the least cost under different scenarios, considering carbon tax and two types of low-carbon technologies (FCS and CCS). The main conclusions of this study are as follows.

(1) The YRDR power system could achieve a carbon peak in 2030 but may not be able to achieve carbon neutrality in 2060 without certain measures. The installed capacity of solar power is expected to increase rapidly from 2020 to 2060, accounting for more than half of the total installed capacity by 2060.
(2) A carbon tax alone might not have a significant impact on carbon emissions until it reaches a sufficiently high level (with a growth rate exceeding 9 %). However, it can promote the development of low-carbon technologies. Increasing FCS and installing CCS technology can achieve effective emission reductions, especially for FCS, contributing to nearly 88 % CO_2 reduction in the carbon neutrality scenario.
(3) A high share of renewable energy can promote carbon neutrality; however, it also leads to excessive pressure on power imports from other regions, making the total system more expensive.

These conclusions suggest a reference pathway for policymakers to determine how existing power generation technologies, low-carbon technologies, and carbon tax policies can achieve a low-carbon transformation of the electricity system. Based on these conclusions, the policy recommendations are as follows:

On the one hand, the YRDR should develop renewable energy according to the conditions of the sub-regions. On the other hand, it is necessary to increase investment in UHV transmission lines and expand the power transmission capacity so that electricity generated by renewable energy sources from other regions can be transmitted to the YRDR.

Although low-carbon technologies such as CCS are currently expensive, their initial development can be promoted by implementing an appropriate carbon tax. Police makers should also note that CO_2 reduction cannot be regulated solely by carbon tax policies or low-carbon technologies. The primary methods for achieving carbon neutrality include using renewable energy, implementing carbon tax policies, and adopting low-carbon technologies. The YRDR's power system could be transformed appropriately toward a carbon-neutral system by comprehensively implementing these measures, ensuring a safer power supply for the socioeconomic system.

As one of the richest regions in China, the YRDR is expected to achieve carbon neutrality. The technology portfolio pathway proposed in this study may serve as a conservative strategy for achieving carbon neutrality in the YRDR power system. However, it is important to acknowledge that this pathway may change with the increased adoption of CDR technologies, flexible resources, and other advancements. These advancements could help achieve carbon neutrality in the YRDR power system earlier, presenting an avenue for further research.

With the increasing penetration of renewable energy sources, especially wind and solar photovoltaic (PV) power, coal-fired power plants are expected to reduce their operation hours in the future. A limitation of this study is that it did not consider the reduction in power plants' O&M costs. Another limitation of this study is that it did not consider CO_2 emissions from imported electricity. In our future work, we will explore scenarios that consider the dynamics of O&M costs for coal-fired power plants, as well as the emission factor of imported electricity.

The model in this study takes a long-term perspective; thus, it does not address peak or valley loads via flexible resources, such as battery energy storage, virtual power plants, and so on. Integrating long and short-term energy system models (i.e., considering the load curves of 8760 h) remains a topic for future research.

CRediT authorship contribution statement

Yaru Zhang: Writing – original draft, Visualization, Software, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Tieju Ma:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Yadong Yu:** Resources, Conceptualization. **Hongtao Ren:** Software, Methodology, Conceptualization.

Ethics statements

Not applicable because this work does not involve the use of animal or human subjects.

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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Appendix A

Fig. A1 shows the power generation structure in the YRDR under the BAU scenario (S-I). The optimized results indicate that the share of renewable energy in power generation is expected to increase rapidly to 45.8 % by 2060. This share is even higher in Anhui Province, reaching 57 % by 2060 (Fig. A1 AH). The share of non-renewable energy in the power system will decrease from 51.9 % in 2020 to 34.8 % in 2060. Coal-fired power generation will still be the main power generation technology in the YRDR until 2060, especially coal-fired power technologies with extra-large sizes (PPXL), which will become major options in the future for each sub-region (see Fig. A1 AH, JS, SH, ZJ). Moreover, small coal-fired power plants (PPS) will gradually be phased out of the power system. Electricity imports from other provinces, such as Shanghai, will also play a key role in the YRDR in the future, reaching 52 % of the total electricity demand in 2060. Compared with other sub-regions in the YRDR, wind power will have a greater advantage in Jiangsu (see Fig. A1 JS).

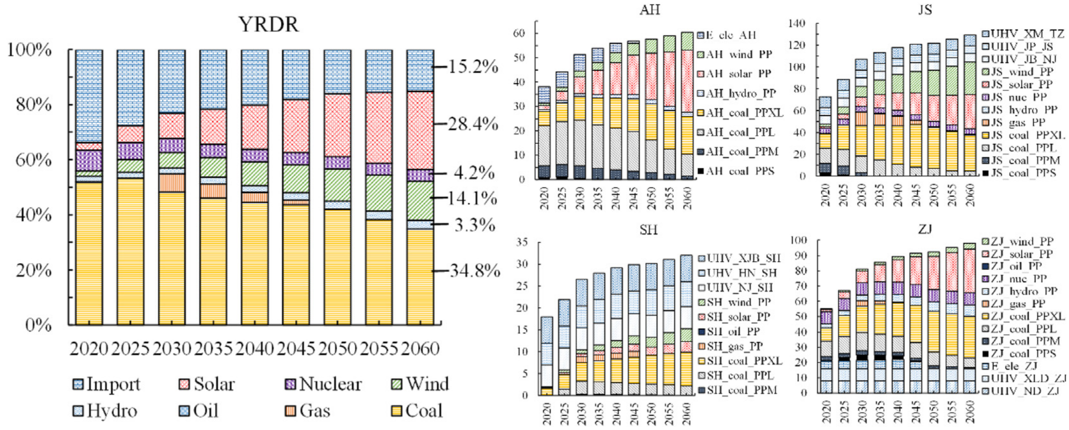

Fig. A1. Power generation mix in the BAU scenario

Appendix B

Fig. B1 shows the total installed capacity of the power plants under the BAU scenario. The total installed capacity of non-renewable power generation technologies is expected to peak around 2030, reaching 298.5 GW, after which it is expected to decline steadily. Renewable power generation technologies are expected to play an important role after 2030. The installed capacity of solar power is expected to increase rapidly from 2020 to 2060, accounting for 58.6 % (721 GW) of the YRDR's total power capacity by 2060. Wind power is expected to grow rapidly after 2030, accounting for approximately 15.8 % (194 GW) of the total power capacity. Owing to the YRDR's resource endowment limitation, the installed hydropower capacity will steadily increase to 52 GW by 2060. Furthermore, nuclear siting potentials are limited by geographic factors, such as distance to coastal areas and elevation drops (Peng et al., 2022); therefore, nuclear power capacity is assumed to be maintained at 14.6 GW by 2060.

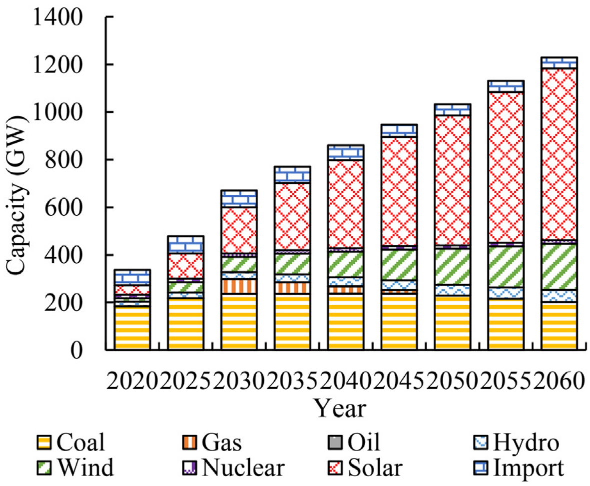

Fig. B1. Total installed capacity of power plants under the BAU scenario

Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jmse.2025.03.001.

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