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Full-length article

Joint electricity and carbon market for Northeast Asia energy interconnection

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Abstract: Decarbonization of the electricity sector is crucial to mitigate the impacts of climate change and global warming over the coming decades. The key challenges for achieving this goal are carbon emission trading and electricity sector regulation, which are also the major components of the carbon and electricity markets, respectively. In this paper, a joint electricity and carbon market model is proposed to investigate the relationships between electricity price, carbon price, and electricity generation capacity, thereby identifying pathways toward a renewable energy transition under the transactional energy interconnection framework. The proposed model is a dynamically iterative optimization model consisting of upper-level and lower-level models. The upper-level model optimizes power generation and obtains the electricity price, which drives the lower-level model to update the carbon price and electricity generation capacity. The proposed model is verified using the Northeast Asia power grid. The results show that increasing carbon price will result in increased electricity price, along with further increases in renewable energy generation capacity in the following period. This increase in renewable energy generation will reduce reliance on carbon-emitting energy sources, and hence the carbon price will decline. Moreover, the interconnection among zones in the Northeast Asia power grid will enable reasonable allocation of zonal power generation. Carbon capture and storage (CCS) will be an effective technology to reduce the carbon emissions and further realize the emission reduction targets in 2030-2050. It eases the stress of realizing the energy transition because of the less urgency to install additional renewable energy capacity.

Keywords: Joint electricity and carbon market, Northeast Asia Energy Interconnection, Dynamically iterative optimization model.

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1 Introduction

Climate change and global warming, caused by emission of greenhouse gases as the byproducts of fossil energy consumption, are becoming major challenges that impede sustainable economic and social development [1-3]. It is reported that the atmospheric concentration of greenhouse gases reached 414.7 parts per million (ppm) in 2019, which was the highest level ever [4]. At the same time, global average temperature exceeded pre-industrial levels by 1.1 °C [1], resulting in increasingly extreme climatic events and natural disasters. Therefore, actively mitigating climate change and promoting low-carbon development have gained consensus among the international community [5-6].

It is undisputable that the emissions generated by fossil energy are the greatest contributor to global warming, especially CO_2 emissions from the use of fossil energy [7-8]. Thus, reducing these emissions from fossil energy is critical for limiting the increase in global average temperature to less than 2 °C above preindustrial levels, as specified in the Paris climate agreement [9-11]. There are two main approaches to controlling carbon emissions: transition from fossil fuels to low-carbon energy sources on the supply side, and reduction of CO_2 emissions by various end-use sectors on the demand side [12]. In addition, carbon markets also can be regarded as an effective tool [13]. As the largest source of emissions by sector, the electricity industry will experience great pressure in terms of both internal operating mechanisms and external environments. Therefore, in a carbon-constrained world, policy makers worldwide should consider both carbon markets and electricity markets.

As the effective methods of controlling climate change and global warming, the carbon market and electricity market have been researched widely by many scholars. For the former, carbon tax, forest carbon sinks, green electricity certificate trading clean development mechanism (CDM), and Emission Trading Scheme (ETS) may be the efficient ways to reduce CO_2 emissions, such as carbon tax studied by different perspectives in [14-15]; [16-17] studied on carbon sinks in Philippines uplands and EU, respectively; [18] reviewed on increasing share of renewable energy by green electricity certificate trading system and [19] established a case study for green certificate trading system. The CDM was investigated in many developing countries or newly developed countries such as Korea and Malaysia in [20]. ETS was studied from an enterprise level [21], and macro level [22]. For the part of the electricity market, the efficiency of generation, transmission and utilization [23], the production sources of electricity [24], and the technology in the processes of electricity distribution, transmission, and utility [25] are now relatively key factors for emissions reduction. Some scholars studied the efficiency of generation, transmission and utilization from the electricity service-side such as integrated carbon capture and storage [26] and renewable and nuclear energy technologies [27], and electricity demand-side such as electrifying transportation and heating sectors [28]. It was found that to implement home-based micro-generators or centralized renewable energy plants could help to cut down the foot-prints in the electricity sector [29]. Some scholars hold the opinion that renewable energy electricity will necessarily contribute to lesser carbon emissions [30-31]. There was also evidence that carbon emission reduction could be realized through technological advancements in the processes of electricity distribution, transmission, and utility, such as electric energy storage [32], the efficiency of electric equipment and facilities, and Plug-in Hybrid Electric Vehicles [33].

However, the carbon market and electricity market operated independently and lacked effective coordination, which seriously restricted the sustainable development of global energy and was not conducive to reducing emissions. Fortunately, in recent years, the development rapidly and connection closely between the electricity market and carbon market make it possible to study the joint electricity and carbon market. Since the 1990s, due to the reform of electricity marketization, the transnational electricity market was emerging. For example, the EU has established its transnational electricity market since 2000, which has expanded from the four northern European countries to the many countries of the European continent, and has now formed a transnational electricity market covering 31 countries, 530 million people [34]. Besides, the number and size of carbon markets in the world are growing, and different carbon markets have shown a trend towards cooperation [35]. For instance, a joint carbon market has been established between the U.S. and Canada; the carbon market of the EU and the Swiss are promoting market connection; a plan of the joint carbon market between China, Japan and South Korea is also under discussion.

The connection between electricity market and carbon market is mainly in three aspects: 1) as the largest share of carbon emissions, the electricity industry is the main participant of carbon market; 2) many countries are promoting electricity marketization and establishing carbon market simultaneously; 3) there is a strong correlation between electricity price and carbon price. Those conditions have provided an opportunity for the study of joint electricity and carbon market. In addition, most of the existing research only focused on the joint electricity and carbon market from electricity market or carbon market, respectively. Indeed, neglecting the impact of any market may lead to an imperfect model which will weaken the role of joint electricity and carbon market in controlling carbon emissions and global warming. Compared with the previous model considering only carbon market or electricity market, this paper explores the relationship between joint electricity and carbon market and development of renewable energy, and establishes a joint electricity and carbon market model, which intends to find the pathways of renewable energy transition under the transactional energy interconnection framework. The contributions of this paper can be summarized as:

A joint electricity and carbon market model is proposed to investigate the relationships between electricity price, carbon price, and power generation capacity.

A pathway toward renewable energy transition is simulated for different zones, based on the Northeast Asia power grid, and the impact of interconnection on the pathway is compared.

The remainder of this article is organized as follows. In Section 2, coupling between electricity and carbon markets is discussed, and a model for a joint electricity and carbon market is proposed. Section 3 presents a case study tested on the Northeast Asia power grid. Section 4 draws main conclusions.

2 Joint electricity and carbon market

2.1 Market coupling of electricity and carbon markets

A joint electricity and carbon market in Northeast Asia would aim to achieve long-term structural change in transnational energy systems, termed a renewable energy transition [36], in which renewables rather than fossil energy would be the main energy sources guaranteeing sufficient capacity to meet energy demand. Essentially, the joint electricity and carbon market is established based on the close connection between electricity markets and carbon markets, especially for the coupling relationship between electricity price and carbon price, as shown in Fig. 1.

It can be observed that a closed relationship exists among the carbon price, electricity price, renewable energy generation, and carbon emission requirements. When carbon prices increase, so do the operation costs of conventional power generation, which forces thermal power plants to raise the electricity price in order to guarantee profitability [37]. A higher electricity price will place thermal power plants at a competitive disadvantage, such that renewable energy plants will supply more load demand because of their lower electricity price [38]. As power generation from renewables takes a larger share than conventional power generation, the need to utilize carbon-emitting energy sources will decline and the carbon price will decrease due to the declining requirement for carbon emission permits [39].

As the main participant in the joint electricity and carbon market, the electricity market consumes more renewable energy because of its lower margin price [40]. This provides a market signal for decision makers to facilitate greater investment in developing renewable energy power plants to

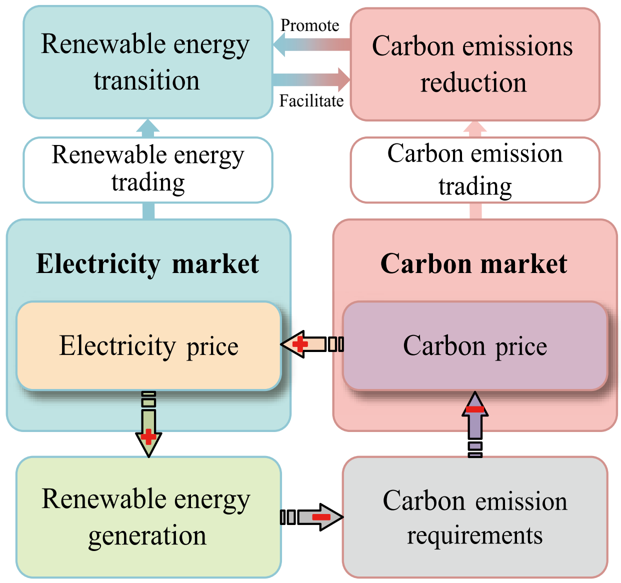

Fig. 1 Market coupling between electricity market and carbon market

pursue higher profits compared with the lower benefits of thermal power plants. Consequently, renewably generated energy will account for a larger share of energy trading in the electricity market, which further motivates the renewable energy transition. Furthermore, carbon emission trading helps participants in the carbon market (i.e., thermal power plants) achieve their carbon emission reduction targets in a more economical way [41]. It should be noted that carbon emission reduction and renewable energy transition are not unconnected but instead closely coupled through the joint electricity and carbon market. In particular, a reduction in carbon emissions will promote the renewable energy transition [42] as aforementioned, and the renewable energy transition will further facilitate the process of carbon emission reduction [43].

2.2 Joint electricity and carbon market model

The electricity price and carbon price are the main driving factors for renewable energy trading and carbon emission trading in the joint electricity and carbon market. Based on this, a joint electricity and carbon market model is proposed to investigate the impact of carbon price on the energy balance and the influence of electricity price on capacity planning. Essentially, the joint electricity and carbon market model is a dynamically iterative optimization model. As shown in Fig. 2, the proposed model consists of nested upper-level and lower-level models. The upper-level model in time t is to optimize energy production and obtain the corresponding electricity price. The lower-level model in time t is to update the carbon price and calculate the capacity of renewable energy, based on the electricity price and optimal energy generation transferred from the upper level. Subsequently, the updated carbon price and renewable energy capacity are fed back into the upper-level model at time t+1, to continue the iterative process until the upper-level model is optimized (at time T).

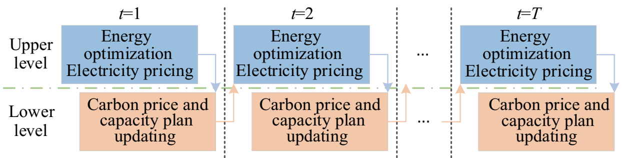

Fig. 2 Framework of dynamically iterative optimization model

2.2.1 Energy optimization and electricity pricing

Fora given time $t \in [1,\cdots,T]$, the upper-level model can be developed as

$$\min \sum_{i=1}^{N_z}(a_i + u_{i,t}\alpha_{i,t})E_{i,t} \tag{1}$$

$$s.t.\ \ E_{i,t} + RE_{i,t} + \sum_{l\in\Omega_i} Y_{l,t} - \sum_{l\in\Phi_i} Y_{l,t} = D_{i,t},\ i=1,\dots,N_z \tag{2}$$

$$-Y_{l,\max} \leqslant Y_{l,t} \leqslant Y_{l,\max},\ l=1,\dots,N_l \tag{3}$$

$$0 \leqslant E_{i,t} \leqslant P_{i,t}h_{i,t},\ i=1,\dots,N_z \tag{4}$$

$$0 \leqslant RE_{i,t} \leqslant R_{i,t}hr_{i,t},\ i=1,\dots,N_z \tag{5}$$

The objective function minimizes the total cost over a period, including the operational cost and carbon emission cost of conventional power generation in all zones, where N_z is the number of zones. $E_{i,t}$, a_i, $u_{i,t}$, and $\alpha_{i,t}$ are the power generation of fossil-fueled generation units, fuel cost coefficients, carbon price, and carbon emission factor in zone i at time t, respectively. The generation and load demand should be balanced at each time period as (2) saying. $RE_{i,t}$ and $D_{i,t}$ are the power generated by renewable energy units and the load demand in zone i at time t. $Y_{l,t}$ is the power generation transferred on tie line l at time t. Parameters Ω_i and Φ_i are the sets of inflows and outflows, respectively, for zone i. N_l is the number of tie lines. The power flow on tie lines should be limited within the allowable range as shown in (3), where $Y_{l,\max}$ is the maximum transmission capacity of tie line l. Equations (4)–(5) represent the power generation limits of the fossil-fueled generation units and renewable energy generation units in each zone over the given period. $P_{i,t}$ and $R_{i,t}$ are the total capacity of conventional power generation units and renewable energy generation units, respectively, in zone i at time t. Parameters $h_{i,t}$ and $hr_{i,t}$ are the annual utilization hours of $P_{i,t}$ and $R_{i,t}$.

The optimal power generation in each zone and transferred power generation among zones can be obtained by solving the proposed model (1)–(5). The model also allows calculation of the electricity price. Define the multipliers corresponding to the constraints of equations (2)–(5), giving

$$\begin{cases} -Y_{l,\max} \leqslant Y_{l,t} \leqslant Y_{l,\max}:\ (\mu_{l,t}^-, \mu_{l,t}^+) \\ E_{i,t} + R_{i,t} + \sum_{l\in\Omega_i} Y_{l,t} - \sum_{l\in\Phi_i} Y_{l,t} = D_{i,t}:\ \lambda_{i,t} \\ 0 \leqslant E_{i,t} \leqslant P_{i,t}h_{i,t}:\ (\gamma_{i,t}^-, \gamma_{i,t}^+) \\ 0 \leqslant RE_{i,t} \leqslant R_{i,t}hr_{i,t}:\ (\vartheta_{i,t}^-, \vartheta_{i,t}^+) \end{cases} \tag{6}$$

Moreover, the Lagrange function of model (1)–(5) is shown as:

$$\begin{aligned} W = &\sum_{i=1}^{N_z}(a_i + u_{i,t}\alpha_{i,t})E_{i,t} \\ &+ \sum_{l=1}^{N_l}\mu_{l,t}^-(-Y_{l,\max} - Y_{l,t}) + \sum_{l=1}^{N_l}\mu_{l,t}^+(Y_{l,t} - Y_{l,\max}) \\ &+ \sum_{i=1}^{N_Z}\gamma_{i,t}^-(0 - E_{i,t}) + \sum_{i=1}^{N_Z}\gamma_{i,t}^+(E_{i,t} - P_{i,t}h_{i,t}) \\ &+ \sum_{i=1}^{N_Z}\vartheta_{i,t}^-(0 - RE_{i,t}) + \sum_{i=1}^{N_Z}\vartheta_{i,t}^+(RE_{i,t} - R_{i,t}hr_{i,t}) \\ &+ \sum_{i=1}^{N_Z}\lambda_{i,t}\left(D_{i,t} - RE_{i,t} - E_{i,t} - \sum_{l\in\Omega_i} Y_{l,t} + \sum_{l\in\Phi_i} Y_{l,t}\right) \end{aligned} \tag{7}$$

The electricity price can be defined as the incremental capacity cost relative to the incremental load demand, such that

$$Electricity\ price_{i,t+1} = \frac{\partial W}{\partial D_{i,t}} = \lambda_{i,t} \tag{8}$$

Note that the electricity price $\lambda_{i,t}$ herein is the electricity price for the current model at time t.

2.2.2 Carbon price and capacity plan updating

With optimal power generation achieved in each zone, the carbon price can be computed by (9), which demonstrates the impact of carbon emission on the carbon price.

$$u_{i,t+1} = u_{i,t} + w_1\left(\frac{\alpha_{i,t}E_{i,t} - C_{i,t}}{C_{i,t}}\right) + \varepsilon,\ i=1,\dots,N_z \tag{9}$$

Here, $u_{i,t+1}$ is the updated carbon price in zone i at time t. $\alpha_{i,t}E_{i,t}$ and $C_{i,t}$ are the carbon emission and the carbon emission targets in zone i at time t. w_1 is the step to quantify the variation of carbon price, and ε is the disturbance of carbon price from external factors including the carbon emissions from fossil fuel consumed by the industrial, construction, and transportation sectors. Obviously, if the carbon emission $\alpha_{i,t}E_{i,t}$ is more than the carbon emission target $C_{i,t}$ at time t, the carbon price in the following period will see a reasonable growth due to the urgent carbon emission requirements. On the other hand, the carbon price at time t+1 will decrease because the carbon emission requirements will be easily satisfied.

Moreover, the zonal capacity of renewable energy generation units and conventional power generation units in the following period can be updated as (10) and (11), respectively.

$$R_{i,t+1} = \max\left(R_{i,t}, \begin{cases} R^0_{i,t+1} + (\lambda_{i,t} - \lambda_{i,t-1}) w_2 hr_{i,t} & , \lambda_{i,t} > \lambda_{i,t-1} \\ R^0_{i,t+1} & , \lambda_{i,t} \leqslant \lambda_{i,t-1} \end{cases} \right), \quad i = 1,...,N_z \tag{10}$$

$$P_{i,t+1} = P^0_{i,t+1}, \ i = 1,...,N_z \tag{11}$$

Here, $R_{i,t+1}$ and $R^0_{i,t+1}$ are the actual capacity and the planned capacity of renewable energy generation units in zone i. $\lambda_{i,t}$ is the optimal electricity price obtained by (6)–(8) at time t, and $\lambda_{i,t-1}$ is the given electricity price $\lambda_{i,0}$ or the electricity price obtained from model at time t-1. Here, $\lambda_{i,t} > \lambda_{i,t-1}$ means that the electricity price increases to hedge against incremental carbon emission cost, which in turn promotes the development of renewable energy generation. w_2 is the step to quantify the incremental capacity of renewable energy generation units. Note that $\lambda_{i,t-1} \leqslant \lambda_{i,t}$ occurs without a reduction in renewable energy capacity, because the planned capacity $R^0_{i,t+1}$ should be guaranteed through long-term planning. Moreover, the updated $R_{i,t+1}$ should not be less than $R_{i,t}$ in practice, because the capacity built at time t could be utilized at time t+1. The actual capacity of conventional power generation units ($P_{i,t+1}$) is set as the planned value ($P^0_{i,t+1}$) as shown in (11).

2.3 Flowchart of the proposed model

It should be noted that there are T subproblems in the proposed model, coupled with the electricity prices, carbon prices, and the capacity of renewable energy generation units. Initially, the optimal power generation by conventional and renewable energy facilities ($E_{i,t}$ and $RE_{i,t}$) are obtained by solving (1)–(5) with the given parameters such as load demand $D_{i,t}$, carbon price $u_{i,t}$, capacity of conventional power generation units $P_{i,t}$, and renewable energy generation units $R_{i,t}$ etc. The carbon price $u_{i,t+1}$ can then be updated by (9), and the capacities of renewable ($R_{i,t+1}$) and conventional ($P_{i,t+1}$) power generation units can be updated with the difference between electricity price $\lambda_{i,t}$ and $\lambda_{i,t-1}$ as shown in (10)–(11). Subsequently, the coupled parameters ($u_{i,t+1}$, $\lambda_{i,t}$, and $R_{i,t+1}$) are delivered to the sequential sub-problem until the final sub-problem at end-time T. Obviously, the optimal solution to each subproblem concerning $E_{i,t}$, $RE_{i,t}$, $P_{i,t+1}$ and $R_{i,t+1}$ will form a pathway for energy transition. The whole flowchart is shown as Table1.

Table 1 Flowchart for a joint electricity and carbon market model

1:	Initialize: $t \leftarrow 1$, T, a_i, w_1, w_2, ε; $\lambda_{i,0}$, $u_{i,t}$, $P_{i,t}$, $R_{i,t}$ for each i; $\alpha_{i,t}$, $D_{i,t}$, $C_{i,t}$, $h_{i,t}$, $hr_{i,t}$, $P^0_{i,t}$, $R^0_{i,t}$, for each i and each t
2:	**While** $t \leqslant T$ **do**
3:	**For** i=1,…,N_z **do**
4:	Solve (1)-(5) and compute $\lambda_{i,t}$ by (6)-(8)
5:	Save $E_{i,t}$, $RE_{i,t}$ and $\lambda_{i,t}$
6:	Update $u_{i,t+1}$, $R_{i,t+1}$ and $P_{i,t+1}$ by (9)-(11)
7:	Save $u_{i,t+1}$, $R_{i,t+1}$ and $P_{i,t+1}$
8:	**End For**
9:	$t \leftarrow t+1$
10:	**End While**

3 Case study

Countries in Northeast Asia have close economic relations and strong energy complementarity. With the development of global energy interconnection, they are actively seeking transnational cooperation on electricity trading and carbon emission trading [44]. However, there is no mature transnational electricity market and carbon trading market so far for these transactions. For electricity market, Russia, Republic of Korea, Japan, China and Mongolia have developed a domestic electricity market [45-47]. For carbon market, China has come a long way toward the construction of a carbon-trading market and will launch a national carbon market in 2020. Republic of Korea has developed a national carbon market and Japan has some subnational carbon market [48]. But no regional electricity market or carbon market exists in Northeast Asia, let alone the joint electricity and carbon market.

Therefore, the proposed joint electricity and carbon market model is tested on a planned Northeast Asia power grid where all the participating countries have an interest in enhancing power interconnection within the sub region in order to promote greater renewable energy penetration, reduce the carbon emissions of power systems, and finally realize the renewable energy transition [36]. All the experiments are carried out using Cplex 12.9 decision-optimization software on a computer with an Intel Core 7 CPU (3.60 GHz).

3.1 Experimental setting

The proposed Northeast Asia power grid consists of six major zones, including the Russian Far East (RFE), Mongolia (M), North & Northeast China (NNC), Japan (J), Republic of Korea (ROK) and the Democratic People's Republic of Korea (DPRK). The framework of grid interconnections among the six zones is depicted in Fig. 3 [41]. It is worth noting that the proposed model is a long-term planning problem spanning several decades, from 2020 to 2050, with intervals of one year. In this way, the load demand and carbon emission targets in each zone are shown in Fig. 4 and Fig. 5. Note that not all tie lines are available to transfer generated power at the start time (i.e., 2020), because tie lines RFE-NNC and RFE-ROK will be available in 2030, and tie lines NNC-J in 2040. The tie line transmission capacities are shown in Fig. 6 [49]. Moreover, Fig. 7 reveals the carbon emission factors of each zone in scenarios with and without carbon capture and storage (CCS) [50]. Finally, the initial electricity price and carbon price in each zone are demonstrated in Table 2 [51].

Table 2 Initial electricity price and carbon price in each zone

Zone	Initial value	
	Electricity price ($/kWh)	Carbon price ($/tons)
Russian Far East	0.07	20
Mongolia	0.07	21
North & Northeast China	0.08	35
Japan	0.22	40
DPRK	0.07	26
ROK	0.12	33

Fig. 3 Framework of Northeast Asia power grid interconnection

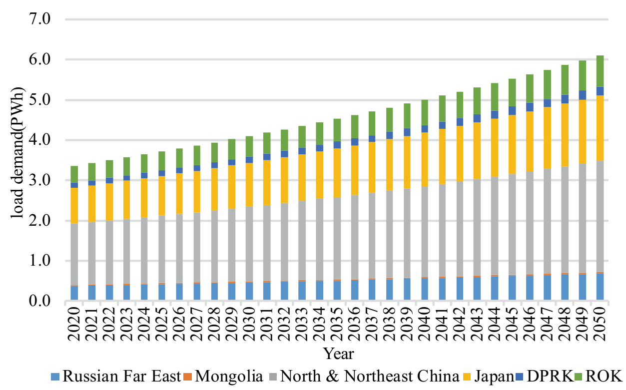

Fig. 4 Load demand of Northeast Asia from 2020 to 2050

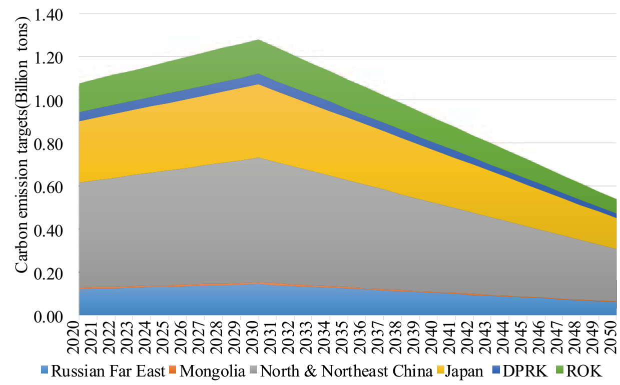

Fig. 5 Carbon emission targets of Northeast Asia from 2020 to 2050

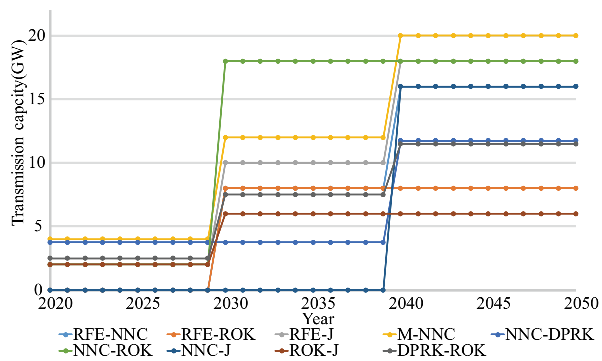

Fig. 6 Transmission capacity in tie lines among six zones

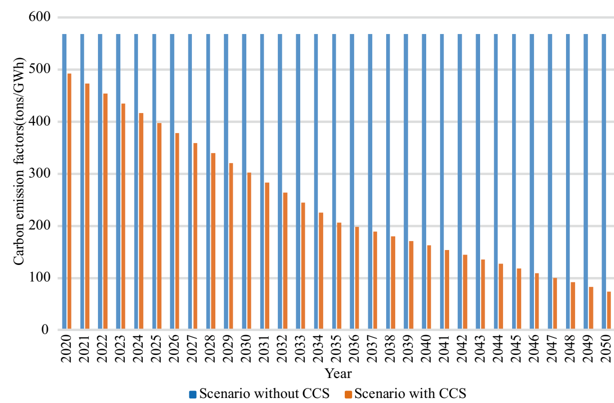

Fig. 7 Carbon emission factors in scenarios with and without CCS

3.2 Results

The electricity price, carbon price, and installed capacity in each zone of the Northeast Asia power grid from 2020 to 2050 are shown in Fig. 8 with steps w_1 and w_2 set as 2 and 30, respectively.

As shown in Fig. 8(a), the electricity price and carbon price in the Russian Far East reveal a smooth trend from 2020 to 2040, with only a small fluctuation in 2022 that causes a visible increase for the planned capacity of renewable energy generation. This is because the capacity and power generation of thermal power generation and renewable energy are developed gradually. However, the capacity of renewable energy generation increases sharply in 2042 because of the incremental electricity price during the previous year, and the following years see a sharp drop in electricity price (even to zero) due to sufficient renewable energy generation. As a result, the carbon price gradually declines.

Fig. 8(b) shows the electricity price, carbon price, and capacity in Mongolia. Obviously, the trends for electricity price and carbon price are similar. However, they do not monotonically decrease over the whole period, but increase visibly from 2020 to 2032. Actually, the carbon price increases in this period due to the transferred power demand of North & Northeast China, as shown in Fig. 9. Much more thermal power is generated in Mongolia with less cost to supply the power shortage of North & Northeast China. After that, carbon price and electricity price reduce as soon as the transferred power from Mongolia to North & Northeast China decreases.

Fig. 8(c) shows a strong coupling relationship between electricity price and carbon price in North & Northeast China. That is, electricity price volatility is always behind that of carbon price volatility, but keeps the same trade as carbon price over the whole period. During the early period of the modeled period (approximately 2020 to 2040), renewable energy capacity in North & Northeast China reaches a much higher level than in other zones, which in turn cuts thermal power generation and further decreases the prices of carbon and electricity. An interesting condition occurs, wherein the total combined capacity of thermal power generation and renewable energy generation is decreasing during this period. This is because the capacity of renewable energy generation remains same, but fossil capacity decreases gradually as planned, which means that the sufficient renewable energy generation enables North & Northeast China to achieve its carbon emission targets much more easily without the need to install more renewable capacity. In the late stage, the carbon emission targets are too strict and carbon price increases again, together with the electricity price. As a result, the capacity of renewable energy generation increases.

A similar condition occurs in Japan and ROK, as shown in Fig. 8(d) and Fig. 8(f): The capacity of thermal power generation and renewable energy generation develops as planned, and electricity and carbon prices decrease gradually in the early stage as expected, but decline slightly faster during 2030 to 2050. This is because the transmission capacity of tie lines RFE-J, ROK-J, DPRK-ROK, and NNC-ROK are expanded 5, 3, 3 and 9 times, as shown in Fig. 6. More generation is transferred into Japan and ROK, and self-produced thermal power generation decreases, which results in declining carbon and electricity prices. Fig. 8(e) reveals the relationships between electricity price, carbon price, and capacity in DPRK. The same process as North & Northeast China occurs in DPRK during the periods 2020–2037, 2038–2047, and 2048–2050.

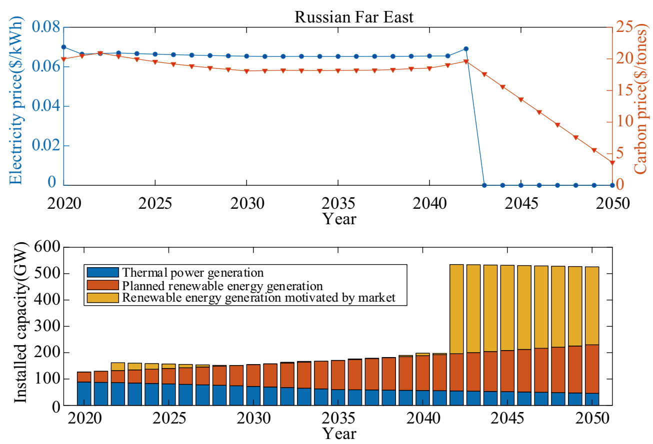

Fig. 8(a) Electricity price, carbon price, and installed capacity in Russian Far East

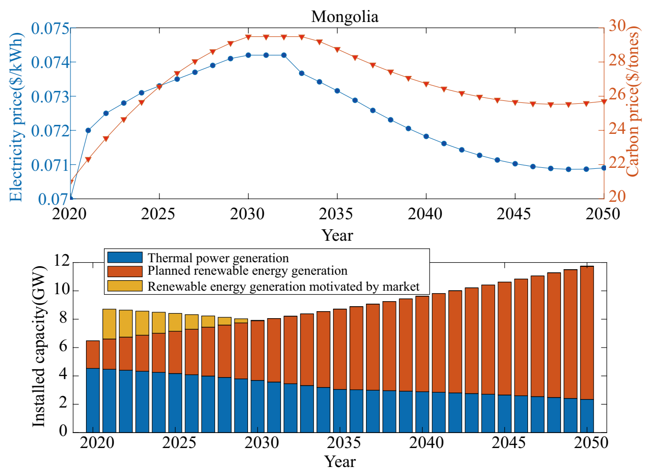

Fig. 8(b) Electricity price, carbon price, and installed capacity in Mongolia

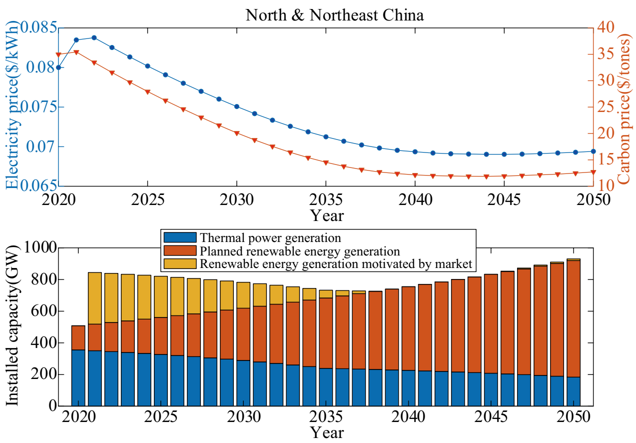

Fig. 8(c) Electricity price, carbon price, and installed capacity in North & Northeast China

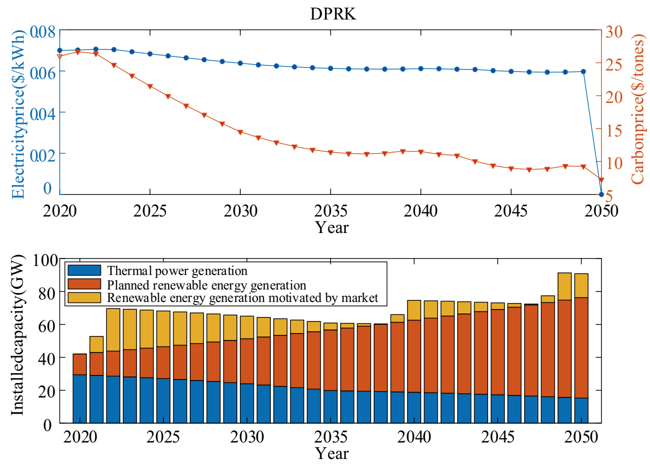

Fig. 8(e) Electricity price, carbon price, and installed capacity in DPRK

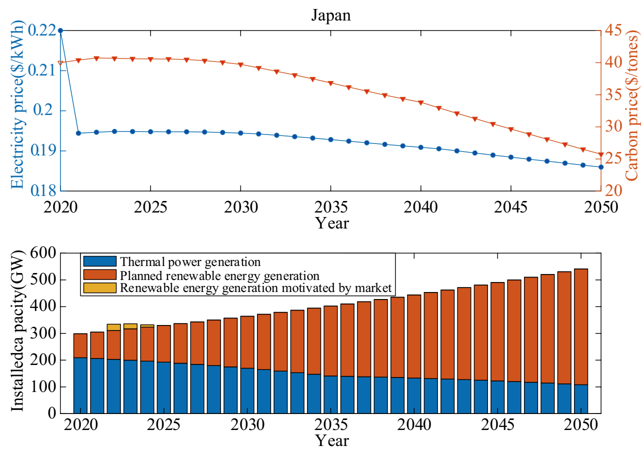

Fig. 8(d) Electricity price, carbon price, and installed capacity in Japan

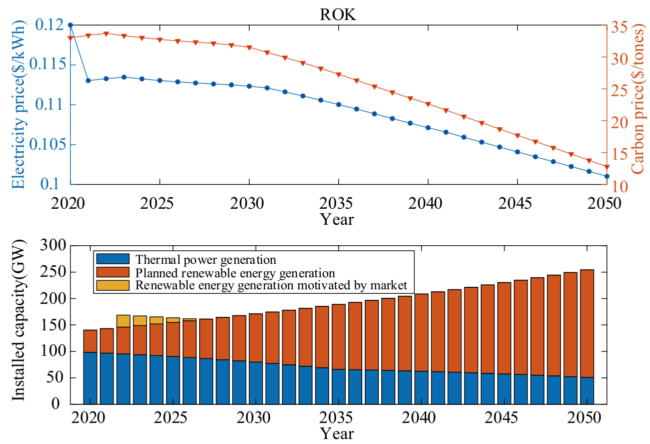

Fig. 8(f) Electricity price, carbon price, and installed capacity in ROK

Obviously, the tie lines play a vital role in maintaining the power balance among the six zones, and further influence the structure of electricity production. Fig. 9 shows the direction of transfer and the approximate power generation in the tie lines. Fig. 10 shows the zonal power generation in two scenarios, namely with and without interconnection.

As shown in Fig. 10(a), there is an apparent difference in the Russian Far East zone between the two scenarios (with and without interconnection). In the early stage, thermal power generation and renewable energy generation do not appear much different between the two scenarios because the RFE-NNC and RFE-DPRK tie line are not operational until 2030, and the capacity of the existing tie ling RFE-J is not sufficient to produce an obvious difference. However, during the period from 2030 to 2040, tie line RFE-NNC is available and RFE-J is expanded for the Russian Far East to transfer more power generation to North & Northeast China and Japan. Note that thermal power generation increases in this period due to the interconnection, because marginal cost in the Russian Far East is lowest compared with the other two zones. After that, the renewable energy generation shows a rapid increase 2041, as shown in Fig. 8(a) and much more power is generated from renewables compared with the scenario without interconnection. It is obvious that renewable energy generation satisfies the load demand of the Russian Far East zone, and surplus power generation is transferred to North & Northeast China, Japan,

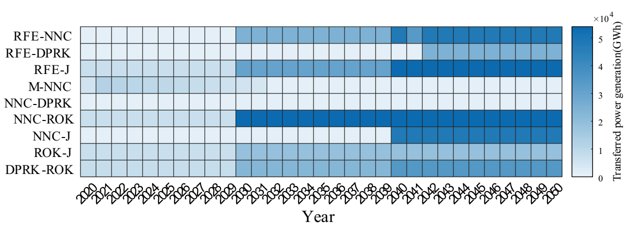

Fig. 9 Transferred power generation in tie lines

and DPRK in the scenario with interconnection. That is to say, interconnection enables the Russian Far East zone to accelerate the process of replacing traditional energy with renewable energy, even realizing "net zero" carbon emissions before 2050.

For Mongolia, as shown in Fig. 10(b), the most apparent difference between two scenarios occurs during the period from 2020 to 2030, in which much more power is generated in the scenario with interconnection, to supply the load demand of Mongolia and North & Northeast China through M-NNC. Subsequently, the power transferred from Mongolia to North & Northeast China declines to zero because sufficient generation capacity is set up in North & Northeast China, after which power generation remains the same in the two scenarios.

Fig. 10(c), Fig. 10(d), and Fig. 10(f) reveal power generation under the two scenarios in North & Northeast China, Japan, and ROK, respectively. Prior to 2030, ROK generates slightly more thermal power to supply Japan through ROK-J in the scenario with interconnection. Apart from this, power generation in the three zones is roughly consistent in the scenarios with and without interconnection. However, compared with the scenario without interconnection, thermal power generation in North & Northeast China and the Russian Far East increases to satisfy the load demand in ROK and Japan by tie line NNC-ROK and RFE-J, respectively, from 2030 to 2040. As a result, thermal power generation in ROK and Japan decreases. After 2040, more power generation is transferred into Japan by NNC-J, which causes a further decline in thermal power generation in Japan. Power generation in ROK is influenced by the power transferred from DPRK, but the difference is visible from the graphs.

It can be observed in Fig. 10(e) that the interconnections between zones have an obvious impact on the power generation of DPRK. Prior to 2040, tie line DPRK-ROK transfers more power generation to ROK in the scenario with interconnection. There is also a slight increase in thermal power generation in 2030 because of the capacity expansion for DPRK-ROK. After that, with the increasing capacity provided by renewables, much more power generation is transferred while satisfying demand in the DPRK.

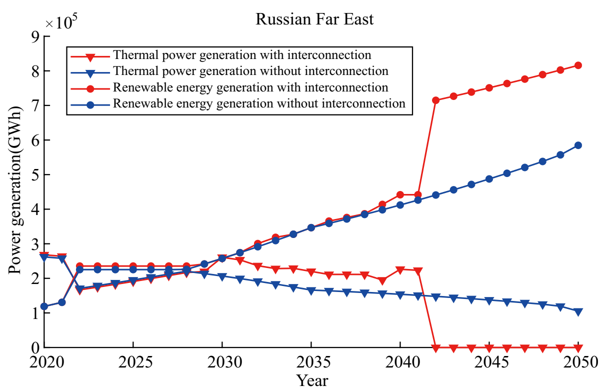

Fig. 10(a) Power generation in Russian Far East with and without interconnection

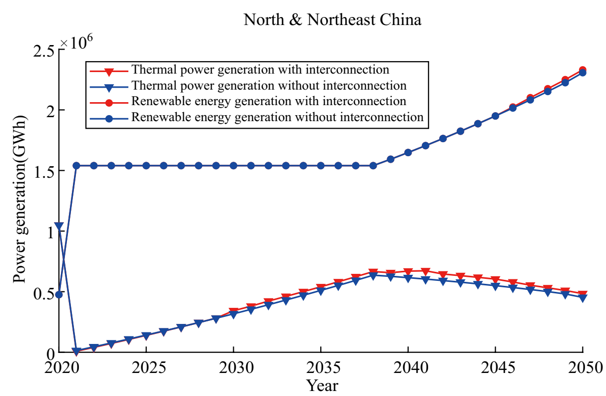

Fig. 10(c) Power generation in North & Northeast China with and without interconnection

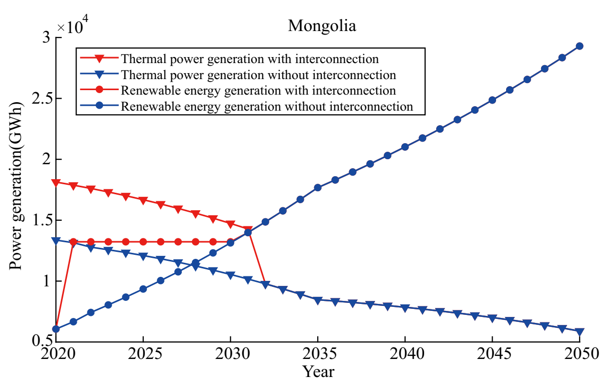

Fig. 10(b) Power generation in Mongolia with and without interconnection

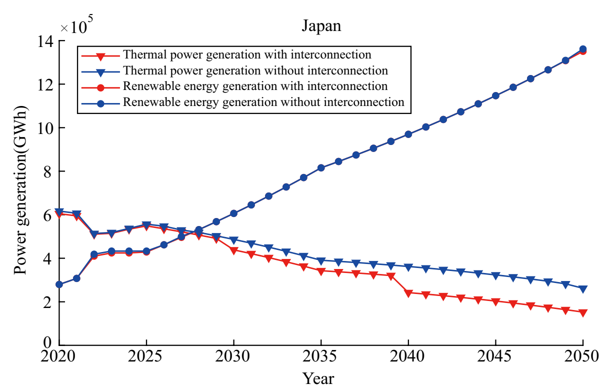

Fig. 10(d) Power generation in Japan with and without interconnection

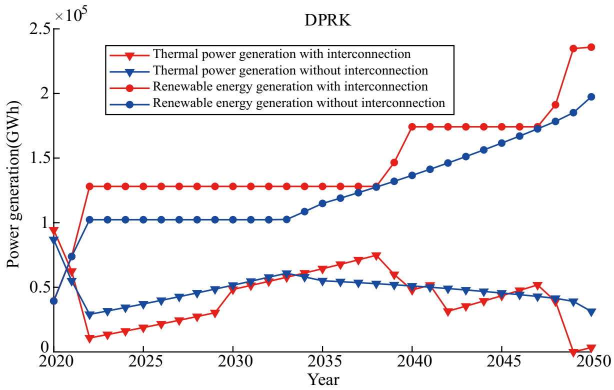

Fig. 10(e) Power generation in DPRK with and without interconnection

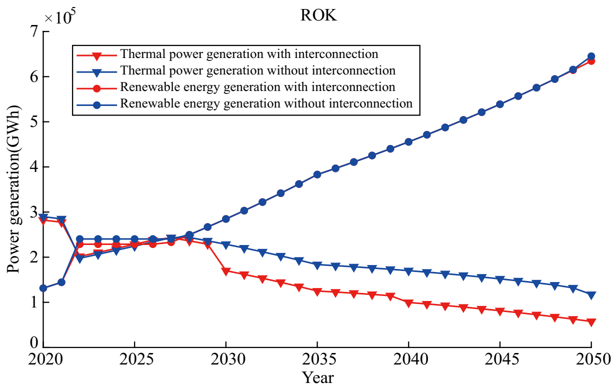

Fig. 10(f) Power generation in ROK with and without interconnection

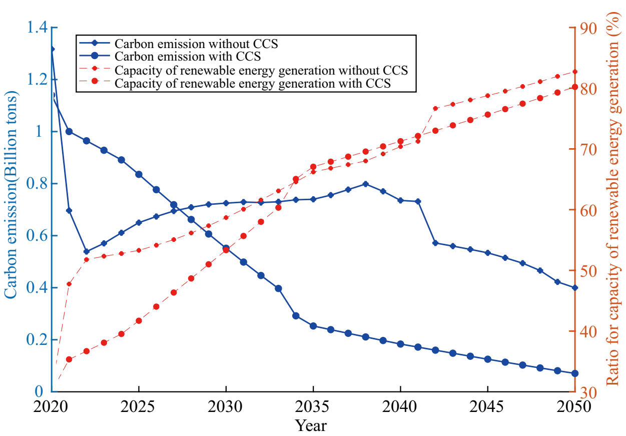

Fig. 11 Carbon emissions and capacity ratio of renewable energy generation with and without CCS

Finally, the carbon emission in scenarios with and without CCS, as well as the impact on the structure of electricity production, are shown in Fig. 11. It can be observed that the carbon emission decreases from 0.40 billion tons in the scenario without CCS, to 0.07 billion tons in the scenario with CCS in 2050. This is an obvious outcome of incorporating CCS, but a more important effect is that it eases the stress of realizing the energy transition, because the CCS scenario requires only 80.21% of renewable energy generation capacity compared with 82.72% in the scenario without CCS. In other words, there is less urgency to install additional renewable energy capacity in order to meet the emission reduction targets.

4 Conclusions

Based on the market coupling of electricity and carbon markets, this paper proposed a joint electricity and carbon market model to identify potential pathways to a renewable energy transition under the transactional energy interconnection framework. The proposed model is a dynamically iterative optimization model consisting of upper-and lower-level models. The upper-level model optimizes power generation and obtains electricity price, whereas the lower-level model updates the carbon price and the capacities of thermal power and renewable energy generation. The proposed model is verified on the Northeast Asia power grid. The results show that interconnection among the network zones will enable zonal power generation to be allocated in a reasonable way. CCS will significantly reduce the carbon emissions in 2030-2050 which helps reduce the stresses on realizing the energy transition by limiting capacity additions of renewable energy. Essentially, the proposed model presents a practical solution for joint electricity and carbon market which will be a helpful model for policymakers when developing the energy transition pathway. Low carbon technologies, e.g. CCS, can be an effective supplement for policymakers to further reduce carbon emission. In the future, the carbon emission from industrial, construction and transportation sectors will be discussed in detail in the joint electricity and carbon market model.

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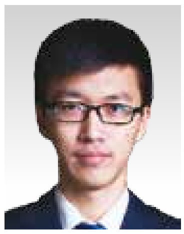

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