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An Optimization-Based Study to Analyze the Impacts of Clean Energy and Carbon Emission Mechanisms on Inter-Regional Energy Exchange

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ABSTRACT. The construction of China's smart grid mainly focuses on the development of the ultra-high voltage line, which benefits the inter-regional energy transmission. The inter-regional energy exchange can promote the development of the energy industry in West China where there is an economic backwardness; at the same time it can reduce the pressure of energy supply and environment protection in East China with a well-developed economy. To study the impacts of clean energy and carbon emission mechanisms on the inter-regional energy exchange, two optimization models are first developed with the objectives of minimizing the generation cost and the carbon emission cost, respectively. Then an integrated optimization model is established through incorporating the aforementioned two models within a general framework, with the objective of minimizing the overall cost. The results indicate that the economic efficiency of the clean energy would be higher than that of the conventional energy in the regional energy exchange. Moreover, there would be a difference in the energy exchange's sensitivity to the carbon price gap of the inter-regional energy exchange; setting different carbon prices would effectively guide the inter-regional energy exchange.

Keywords: carbon emission price; clean energy, generation scheduling, inter-regional energy allocation

1. Introduction

The economic development in East China is faster than that in West China, however, a variety of energy sources that support the economic development, including fossil energy (e.g., coal and petroleum) and clean energy (e.g., wind power and solar power), are mainly distributed in the western inland areas. Such a distribution of energy resource and power demand has become a bottleneck that hinders China's economic development. The promotion and application of smart grid and advanced transmission technologies such as extra-high voltage (UHV) and ultra-high voltage (EHV) power transmission have provided a feasible option.

According to the national 12th Five-Year-Period planning for energy technology, the government will promote the construction of the strong UHV grid during the next five years. The blueprint of this planning is to form a trunk network of the UHV grid with the shape of "three vertical and three horizontal" in the northern, eastern and central China, to construct a 750 kV power grid covering the main power demand areas in Northwest China, and to complete the transmission line with the shape of "nine straight eight cross" in South China. The inter-regional power transmission can meet the requirements of coordinating the economic development and the energy demand in different areas, accommodating wind power and solar power in western areas, and reducing the GHG emission and the pollutant discharge. The optimized allocation of power is in essence the optimized allocation of unit commitment, which aims to achieve the dual objectives of economic and environmental efficiency through identifying a desired generation plan of different energy sources, and units with different installed capacities in different regions.

In the past, a number of methods were proposed to deal with unit commitment problems, such as artificial bee colony algorithm (Chandrasekaran et al., 2012), mixed integral quadratic constraint planning (Lopez et al., 2012), imperialism competition algorithm (Hadji and Vahidi, 2012), and particle swarm optimization algorithm (Gaing and Lin, 2011).

To optimize the power generation resource and reduce the environmental pollution, the State Council (2007) promulgated "Energy-saving generation dispatching (Trial)". Liao (2010) and Chen et al. (2012) brought the clean energy generation into the power generation dispatching system, and optimized the dispatching by the Chaotic quantum genetic algorithm and the particle swarm optimization algorithm. Tan et al. (2009a and 2009b) built a TOU pricing joint optimization model on the sides of the power generation and the sales. Based on the analysis of the energy-saving generation dispatching, Gao and Li (2008) discussed the factors that influenced the energy-saving generation dispatching. Wang and Choi (2008)

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Table 1. Nomenclatures for parameters and variables

Notation	Meaning
t	Time period indicator (hrs).
i, j	Area indicator, denoted as transmission area and receiving area, respectively.
m, n, k	Power unit indicator, denoted as fossil energy unit in transmission area, clean energy unit in transmission area and fossil energy unit in receiving area, respectively.
f_{im}, f_{in}, f_{jk}	The coal consumption cost function of units.
R_{im}, R_{in}, R_{jk}	The generation reserve cost function of units.
E_{im}, E_{in}, E_{jk}	The CO_2 emissions function of units.
Δg_{im}^{t}	The increased generating output of fossil energy power unit m in region i in period t.
Δg_{in}^{t}	The increased generating output of clean energy power unit n in region i in period t.
Δg_{jk}^{t}	The decreased generating output of fossil energy power unit k in region j in period t.
g_{im}^{t}	Original generating plan of fossil energy power unit m in region i in period t.
g_{in}^{t}	Original generating plan of clean energy power unit n in region i in period t.
g_{jk}^{t}	Original generating plan of clean energy power unit k in region j in period t.
D_i^t, D_j^t	The power demand in power transmission area i and power receiving area j in period t.
$\Delta D_i^t, \Delta D_j^t$	The increased and decreased power demand in power transmission area i and power receiving area j, respectively.
$\theta_{im}, \theta_{in}, \theta_{jk}$	The auxiliary power ratio of units.
L_{ij}^{t}	The energy loss during the transmitssion from area i to area j.
d_{ij}	Transmission distance between area i and area j.
r	The resistivity of transmission line.
U	The transmission voltage.
g_{im}^{cap}	The maximum generating output of fossil energy power unit m in region i.
g_{in}^{cap}	The maximum generating output of clean energy power unit n in region i.
g_{jk}^{cap}	The maximum generating output of fossil energy power unit k in region j.
ψ_i^t, ψ_i^t	The price on carbon emissions in areas i and j.
a^f, b^f, c^f	Coefficients of the coal consumption cost function.
b^R, c^R	Coefficients of the generation reserve cost function.
b^E, c^E	Coefficients of the CO_2 emissions function.
α_i, β_i	Coefficients of the carbon emissions price function in area i.
α_j, β_j	Coefficients of the carbon emissions price function in area j.

proposed an energy-saving series compensation strategy under the constraints of the injected voltage and the input power. The aforementioned studies mainly focus on the optimization of power allocation, but they hardly take into account the coordinated development of energy in different regions. Wang et al. (1999a and 1999b) established a model for maximizing the inter-regional power exchange, and obtained the results through the successive load flow calculation algorithm. Vlachos and Biskas (2011) proposed a multi-regional power trading model based on the electricity market mechanisms. Chung et al. (2011) developed a cross-regional generation optimization model based on the constraints of the power flow and the units' start and stop, and solved it by using a generalized benders decomposition algorithm. Chitra et al. (2012) used a particle swarm optimization approach to solve a multi-area unit commitment model that considered the transmission losses. In consideration of the impact of environmental factors on dispatching, Jiang et al. (2010) proposed an optimization model for the inter-regional exchange of power generation; this study only focused on the coal-fired units, but it could hardly reflect the benefits of using new energy units in the regional energy optimization.

In this study, three optimization models will be established with different objectives for the inter-regional energy exchange, which takes into account the generation cost, the reserve cost, the transmission cost and the emission cost. These models will be solved through GAMS to explore the economic and environmental benefits of the inter-regional energy exchange. In addition, the benefit of introducing clean energy into the inter-regional energy exchange will be revealed. The guiding effect of carbon price to the inter-regional energy exchange will be explored by developing a carbon price function.

2. Model Development

2.1. Optimization Model for Minimizing the Generation Cost

Generally, the relationship between the coal consumption and the generation output of a thermal power generation unit can be represented by a quadratic function (Carrión and Arroyo, 2006). Assuming that the generating cost function of a regional power unit is:

$$f(g^t) = a^f + b^f \times g^t + c^f \times (g^t)^2 \tag{1}$$

where g^t is the generating output of the plant in period t. The fossil energy is mainly distributed in the western area, while the power receiving area is often far away from the fossil energy origin. Hence, the transportation cost is fairly high. Therefore, the marginal cost of power generation in the power receiving area is higher than that in the power transmission area. The variable cost of renewable energy such as wind power is low, and the power transmitted through the high voltage transmission lines may be abandoned. Therefore, the variable costs of the clean energy power unit can be regarded as zero (Wang and Sun, 2012), namely:

$$b^f = c^f = 0 \tag{2}$$

The power generation reserve cost function of power plant in each region is:

$$R(g^t) = b^R \times g^t + c^R \times (g^t)^2 \tag{3}$$

The higher the output of a power unit is, the higher its reserve cost is, but the available reserve capacity in the power system is relatively decreasing. Therefore, with the generation output of the unit gradually approaching its rated capacity, its marginal cost of the reserve capacity will gradually increase. (Gan and Litvinov, 2003; Chu et al., 2004), namely:

$$mc'_R = \frac{d^2R}{dg^2} = 2 \times c^R > 0 \Rightarrow c^R > 0 \tag{4}$$

Wind power and photovoltaic power generation have the intermittent and instable characteristics; their marginal backup capacity costs are higher than the cost of the conventional energy.

Generally, the proportion of clean energy generators in power receiving areas is relatively small. Therefore, the optimization of the inter-regional power allocation only considers the fossil fuel power generators and the clean energy generators in the feeding areas as well as the fossil fuel generators in the receiving areas. An optimization model (P_1) can be established as follows:

$$\begin{aligned} \min Z_1 = & \sum_t [\sum_m f_{im}(g_{im}^t + \Delta g_{im}^t) + \sum_n f_{in}(g_{in}^t + \Delta g_{in}^t)] \\ & + \sum_t [\sum_k f_{jk}(g_{jk}^t - \Delta g_{jk}^t) + p_{ij}^{tr} \Delta D_i^t] \\ & + \sum_t [\sum_m R_{im}(g_{im}^t + \Delta g_{im}^t) + \sum_n R_{in}(g_{in}^t + \Delta g_{in}^t)] \\ & + \sum_t \sum_k R_{jk}(g_{jk}^t - \Delta g_{jk}^t) \end{aligned} \tag{5a}$$

subject to:

$$\begin{aligned} D_i^t + \Delta D_i^t = & \sum_m [(g_{im}^t + \Delta g_{im}^t)(1 - \theta_{im})] \\ & + \sum_n [(g_{in}^t + \Delta g_{in}^t)(1 - \theta_{in})] \end{aligned} \tag{5b}$$

$$D_j^t - \Delta D_j^t = \sum_k [(g_{jk}^t - \Delta g_{jk}^t)(1 - \theta_{jk})] \tag{5c}$$

$$\Delta D_i^t - L_{ij}^t = \Delta D_j^t \tag{5d}$$

$$L_{ij}^t = d_{ij}(\Delta D_i^t)^2 r / U^2 \tag{5e}$$

$$0 \le g_{im}^t + \Delta g_{im}^t \le g_{im}^{cap} \tag{5f}$$

$$0 \le g_{in}^t + \Delta g_{in}^t \le g_{in}^{cap} \tag{5g}$$

$$0 \le g_{jk}^t - \Delta g_{jk}^t \le g_{jk}^{cap} \tag{5h}$$

$$\Delta g_{im}^t \ge 0\,;\quad \Delta g_{in}^t \ge 0\,;\quad \Delta g_{jk}^t \ge 0 \tag{5i}$$

In the objective function, $\sum_m f_{im}(g_{im}^t + \Delta g_{im}^t)$ represents the overall coal consumption cost of the thermal generator in feeding areas; $\sum_n f_{in}(g_{in}^t + \Delta g_{in}^t)$ represents the overall generation cost of the clean energy generator in feeding areas; $\sum_k f_{jk}(g_{jk}^t - \Delta g_{jk}^t)$ represents the overall coal consumption cost in receiving areas; $p_{ij}^{tr} \Delta D_i^t$ represents the transmission cost; $\sum_m R_{im}(g_{im}^t + \Delta g_{im}^t)$ represents the overall reserve cost of the thermal generators in feeding areas; $\sum_n R_{in}(g_{in}^t + \Delta g_{in}^t)$ represents the overall reserve cost of the clean energy generators in feeding areas; $\sum_k R_{jk}(g_{jk}^t - \Delta g_{jk}^t)$ represents the overall reserve cost of the thermal generators in receiving areas.

With respect to the constraints, equation (5b) describes the equilibrium load constraints of the power feeding areas. The power generated from the feeding areas should not only meet the local demand, but also satisfy that of the receiving areas. Equation (5c) describes the equilibrium load constraints of the power receiving areas. The power demand in the receiving areas would be met by the power generated locally and that from the feeding areas. Equation (5d) describes the transmission loss constraints. Due to the transmission loss, the rate of power in receiving areas is lower than that of the feeding areas. Equation (5e) describes the calculation formula of the transmission loss. The transmission loss is subject to the transmission distance, the transmission power, the resistivity of the transmission line and the transmission pressure. Inequalities (5f) to (5h) describe the real time generation constraints. The real time generation of a unit should be within its rated capacity. Inequality (5i) describes the non-negativity constraints. Decision variables, denoted as Δg_{im}^{t1}, Δg_{in}^{t1} and Δg_{jk}^{t1}, can be obtained by solving model (P_1).

2.2. Optimization Model for Minimizing the Environmental Cost

The CO_2 emission of a thermal unit is subject to its unit generation coal consumption. Therefore, the CO_2 emission of a thermal unit can be calculated by a quadratic function of its generation output. Assuming that the CO_2 emission function of a regional power unit is:

$$E(g^t) = b^E \times g^t + c^E \times (g^t)^2 \tag{6}$$

For clean energy, their emission amounts can be considered as zero, namely:

$$b^E = c^E = 0 \tag{7}$$

In the past, the generation scheduling optimization models that considered the environmental constraints generally aimed to minimize the gross emission. Such models may lose the valuable information regarding the difference of emission reduction benefits among different regions. Greenhouse gas emissions are related to many factors, such as regional population, GDP per capita, and environmental values (Vargas-

Table 2. Generation Scheduling and Correlation Coefficients of Units

Area	Unit	P (MW)	Plan (MWh)	Service power	Generating cost		Reserve cost		CO$_2$ emission		
					a^f	b^f	c^f	b^R	c^R	b^E	c^E
A_1	11-coal	600	540	5.70%	5.18	0.0232	-2.1E-06	0.0024	9.0E-07	0.941	-4.3E-05
	12-coal	400	370	7.20%	3.22	0.0243	-3.3E-06	0.0023	1.1E-06	0.936	-8.2E-05
	13-coal	300	250	7.70%	2.45	0.0239	-2.8E-06	0.0025	2.1E-06	0.975	-1.3E-04
	14-coal	300	220	6.80%	2.57	0.0241	-4.1E-06	0.0022	1.5E-06	0.993	-1.1E-04
	15-coal	200	180	5.20%	2.03	0.0247	-6.4E-06	0.0023	2.6E-06	1.080	-1.8E-04
	16-wind	250	100	2.10%	9.67	0	0	0.0037	3.4E-06	0	0
A_2	21-coal	600	560	6.10%	5.32	0.0321	-2.8E-06	0.0029	1.1E-06	0.935	-4.3E-05
	22-coal	600	370	5.30%	5.48	0.0328	-3.5E-06	0.0028	9.1E-07	0.921	-5.1E-05
	23-coal	450	320	7.10%	3.91	0.0335	-4.8E-06	0.0026	1.2E-06	0.969	-8.3E-05
	24-coal	300	250	7.50%	2.64	0.0338	-5.6E-06	0.0027	1.8E-06	0.996	-1.2E-04
	25-coal	300	130	6.30%	2.49	0.0341	-6.3E-06	0.0027	2.1E-06	0.992	-1.0E-04
	26-coal	200	100	7.80%	2.26	0.0339	-8.2E-06	0.0025	2.7E-06	1.050	-1.9E-04

Table 3. Coefficients of Carbon Emissions in Different Areas

Area	α	β
A_1	2.0E-06	5.1E-03
A_2	1.3E-06	8.4E-03

Vargas, 2012; Arouri, 2012). The combined effects of these factors can be ultimately reflected in the form of a shadow value through the value mechanism which is generally high in the developed regions and low in less developed regions. Therefore, the carbon price is introduced as one variable to reflect the environmental value of the inter-regional energy exchange. Furthermore, the desulfurization and denitrification technology has matured in China. When the fossil energy power plant installs the desulfurization and denitrification devices, its processing capacity can be more than 90%. In this study, a constraint optimization model (P_2) of the regional emission reduction is developed with the objective of minimizing the cost of CO_2 emissions:

$$\min Z_2 = \sum_t [\psi_i^t \sum_m E_{im}(g_{im}^t + \Delta g_{im}^t) + \psi_j^t \sum_k E_{jk}(g_{jk}^t - \Delta g_{jk}^t)] \tag{8a}$$

subject to: (5b) – (5i)

$$\psi_i^t = \alpha_i \sum_m E_{im}(g_{im}^t + \Delta g_{im}^t) + \beta_i \tag{8b}$$

$$\psi_j^t = \alpha_j \sum_k E_{jk}(g_{jk}^t - \Delta g_{jk}^t) + \beta_i \tag{8c}$$

In the objective function, $\psi_i^t \sum_m E_{im}(g_{im}^t + \Delta g_{im}^t)$ represents the cost of carbon emissions in feeding areas. $\psi_j^t \sum_k E_{jk}(g_{jk}^t - \Delta g_{jk}^t)$ represents the cost of carbon emissions in receiving areas.

Regarding the constraints, equations (8b) and (8c) indicate the linearized demand relation function between the carbon price and the carbon emission. Decision variables, denoted as Δg_{im}^{t2}, Δg_{in}^{t2} and Δg_{jk}^{t2}, can be obtained by solving model (P_2).

2.3. Optimization Model for Minimizing the Overall Cost

Models (P_1) and (P_2) are proposed for minimizing the generation cost and the cost of carbon emissions, respectively. Model (P_3) is then formulated by integrating models (P_1) with (P_2):

$$\min Z_3 = Z_1 + Z_2 \tag{9}$$

subject to: (5b) ~ (5i) and (8b) ~ (8c).

Decision variables, denoted as Δg_{im}^{t3}, Δg_{in}^{t3} and Δg_{jk}^{t3}, can be obtained by solving model (P_3). The overall generating costs in the power transmission and in the receiving area can be respectively obtained by:

$$\begin{aligned} C_i^* = & \sum_t [\sum_m f_{im}(g_{im}^t + \Delta g_{im}^{t3}) + \sum_n f_{in}(g_{in}^t + \Delta g_{in}^{t3}) \\ & + \sum_m R_{im}(g_{im}^t + \Delta g_{im}^{t3}) + \sum_n R_{in}(g_{in}^t + \Delta g_{in}^{t3})] \\ & + \sum_t [\psi_i^t \sum_m E_{im}(g_{im}^t + \Delta g_{im}^{t3})] \end{aligned} \tag{10}$$

and

$$\begin{aligned} C_j^* = & \sum_t [\sum_k f_{jk}(g_{jk}^t - \Delta g_{jk}^{t3}) + \sum_k R_{jk}(g_{jk}^t - \Delta g_{jk}^{t3}) \\ & + \psi_j^t \sum_k E_{jk}(g_{jk}^t - \Delta g_{jk}^{t3})] \end{aligned} \tag{11}$$

The average generating costs in the power transmission and in the receiving area are:

$$p_i^* = C_i^* / \sum_t [\sum_m (g_{im}^t + \Delta g_{im}^{t3}) + \sum_n (g_{in}^t + \Delta g_{in}^{t3})] \tag{12}$$

$$p_j^* = C_j^* / \sum_t \sum_k (g_{jk}^t + \Delta g_{jk}^{t3}) \tag{13}$$

The carbon emission prices of the power transmission in the receiving area in period t are:

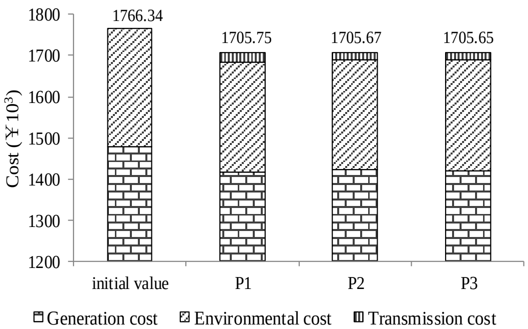

Figure 1. Comparison of various costs under different objectives.

$$\psi_i^t = \alpha_i \sum_k E(g_{im}^t + \Delta g_{im}^{t3}) + \beta_i \tag{14}$$

$$\psi_j^t = \alpha_j \sum_k E(g_{jk}^t - \Delta g_{jk}^{t3}) + \beta_j \tag{15}$$

The overall generation cost after the inter-regional energy exchange would be different, and it can be calculated through the following equation:

$$\begin{aligned} C_{im}^{P3} = \sum_t [& f_{im}(g_{im}^t + \Delta g_{im}^{t3}) + R_{im}(g_{im}^t + \Delta g_{im}^{t3}) \\ & + \psi_i^t E_{im}(g_{im}^t + \Delta g_{im}^{t3})] \end{aligned} \tag{16}$$

$$C_{in}^{P3} = \sum_t [f_{in}(g_{in}^t + \Delta g_{in}^{t3}) + R_{in}(g_{in}^t + \Delta g_{in}^{t3})] \tag{17}$$

$$\begin{aligned} C_{im}^{P3} = \sum_t [& f_{jk}(g_{jk}^t + \Delta g_{jk}^{t3}) + R_{jk}(g_{jk}^t + \Delta g_{jk}^{t3}) \\ & + \psi_j^t E_{jk}(g_{jk}^t + \Delta g_{jk}^{t3})] \end{aligned} \tag{18}$$

3. Case study

3.1 Overview of the Study System

Assuming that there are six power plants in the power feeding area (A_1) and the power receiving area (A_2), including one wind power plant in the feeding area and five thermal power plants. The hourly generation plans, unit conditions, generating cost coefficients, reserve cost coefficients, and CO_2 emission coefficients are provided in Table 2. The correlation coefficient between the transmission loss and the square of transmission capacity is 1.8E-04. The transmission price is ¥70 per MWh. The coefficients of carbon emissions are shown in Table 3.

3.2. Comparative Analysis of Different Optimization Models

The aforementioned models are all nonlinear, and they can be solved through CLPEX solver of GAMS. Since there is no CO_2 emissions during the wind power generating process and the variable cost of wind power can be considered as zero, it would be economically beneficial to accommodate more wind power. As the reserve cost of wind power is fairly low, it would be included in the generation plan in all the three optimization models. As for the coal-fired generation units, the coal consumption costs and the CO_2 emissions are subject to the generation efficiency of the unit. Generally, the generation efficiency of a large-scale unit is higher than that of a small-scale one. Thus, the optimization of the generation plan can be achieved by substituting large units for small ones. The results indicate that the load demand of the power receiving area would be met by replacing small units in the power receiving area with large ones in the power feeding area. For the individual unit, the total cost of units in the power feeding area would increase with the growing generating capacity, and the overall generation cost in the power receiving area would decline with the decrease in the generating capacity. It is revealed that although part of the unit's power plan does not vary, the change in the total power generation causes a concurrent change in the carbon price and the environmental cost.

Figure 1 shows the comparison of the total power generation costs under different objectives. It is indicated that the costs obtained from three optimization models are almost the same; the difference in amplitude would be within ¥100. When comparing the overall cost of the initial power generation plan with the costs obtained from the optimization models, however, the results reveal that their difference is obvious. The overall costs would be reduced by ¥60,590, accounting for 3.44% of the initial cost. For the cost of the power supply, the cost of optimized units would be decreased by ¥61,970 at most, accounting for 4.19% of the initial cost of the power supply; the overall environmental costs of the optimized units would be reduced up to ¥20,390, accounting for 7.08% of the initial environmental costs. Moreover, the transmission costs obtained from three optimization models would be ¥21,410, ¥16,320 and ¥16,980, respectively. In general, the generation cost of model (P_1) would be lowest, while the environmental cost of model (P_2) would be lowest. As for model (P_3), the generation cost and the environmental cost would be at the intermediate level comparing to models (P_1) and (P_2), while its overall cost would be lowest.

Table 4 shows a comparison of the generating costs and the average prices in the power transmission and the receiving areas. The total cost of power generation would increase by optimizing the power transmission area, but the average price of power generation would decline. Although the total cost for power generation in the receiving area declines, the average price of power generation would increase.

3.3. Benefits of Clean Energy in Regional Energy Systems

As shown in Table 5, wind power is incorporated into the power generation plans with different optimization objectives. To study its influence in the regional energy optimization, wind power is not taken into account in model (P_3), and its results are shown in Table 6. All the generating units' plans of the power transmission area would increase and the

Table 4. Comparison of Generating Costs and Average Prices under Different Objectives

Area	Initial value		P_1		P_2		P_3	
	Generating cost (¥10^3)	Average price (¥10^3)	Generating cost (¥10^3)	Average price (¥/MWh)	Generating cost (¥10^3)	Average price (¥/MWh)	Generating cost (¥10^3)	Average price (¥/MWh)
A_1	773.0	465.66	839.7	424.09	812.0	426.90	815.5	426.47
A_2	993.4	574.22	844.6	595.25	877.5	588.97	873.2	589.80

Table 5. Comparison of Optimization Results under Different Objectives

Area	Unit	Initial value		P_1		P_2		P_3	
		Generation plan (MWh)	Overall cost (¥10^3)	Generation plan (MWh)	Overall cost (¥10^3)	Generation plan (MWh)	Overall cost (¥10^3)	Generation plan (MWh)	Overall cost (¥10^3)
A_1	11-coal	540	226.4	+60	247.0	+60	246.2	+60	246.3
	12-coal	370	154.5	+30	165.2	+30	164.7	+30	164.8
	13-coal	250	109.0	-	109.7	+2.1	110.1	-	109.3
	14-coal	220	99.4	+80	126.3	-	99.8	+12.2	103.8
	15-coal	180	82.8	-	83.4	-	83.1	-	83.2
	16-wind	100	100.7	+150	108.1	+150	108.1	+150	108.1
A_2	21-coal	560	297.4	-	295.4	-	295.9	-	295.8
	22-coal	370	218.0	-	216.7	-	217.0	-	217.0
	23-coal	320	182.6	-	181.4	-	181.7	-	181.6
	24-coal	250	140.6	-81.1	103.6	-10.1	135.4	-19.5	131.3
	25-coal	130	85.4	-130	24.9	-130	24.9	-130	24.9
	26-coal	100	69.3	-100	22.6	-100	22.6	-100	22.6

Table 6. Optimization Results of Generation Scheduling without Wind Power

Unit	Area (A_1)					Area (A_2)					
	G11	G12	G13	G14	G15	G21	G22	G23	G24	G25	G26
Generation (MWh)	60	30	48.8	80	20					-130	-100

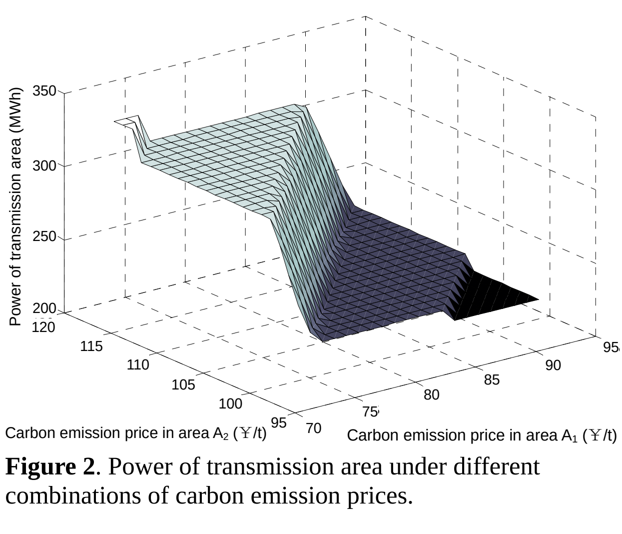

Figure 2. Power of transmission area under different combinations of carbon emission prices.

total generating capacity would increase to 238.8 MWh, which is less than the increased generating capacity of 252.2 MWh when wind power is involved in the regional energy optimization. From the perspective of the power generation cost optimization, the total cost would be ¥1,665,400 and the optimized overall cost would be ¥1,654,600 if wind power is not involved in the regional energy optimization. On the contrary, if only wind power is involved in the regional energy optimization, the overall cost would decrease from ¥1.094 to ¥1.037 million. The results indicate that wind power has a significant contribution of 84.09% to the total cost. Therefore, clean energy plays a significant role in the regional energy optimization.

3.4. Influence of Carbon Price

The initial carbon prices in the power feeding area and in the receiving area are ¥80.38 and ¥105.02 per tonne, respectively. Along with the replacement of CO_2 emission between areas, the carbon prices turns into ¥82.20 and ¥101.79 per tonne. In fact, the inter-regional energy pricing has an impact on the optimization of the inter-regional energy allocation, and it determines the amount of the electric power transmission to a certain extent. As shown in Figure 2, when the initial carbon price tends to be equal in different areas, the market mechanisms of carbon emissions would hinder the energy optimization in the region. The willingness of the power transmission units' involvement in the regional optimization would greatly decrease, and its additional generating capacity would be less than the optimized results of model (P_3). With the expansion of the gap of the carbon emission prices between the power transmission and the receiving area, the output power in the power transmission area would gradually increase. As shown in Figure 2, the carbon emission price of ¥25 ~ 30 per tonne would be the most sensitive interval of the power generation exchange. Within this interval, the increasing generating capacity in the power transmission area would upgrade from 250 to 300 MWh. Therefore, the difference between regional carbon prices would effectively guide the energy optimization and promote the inter-regional transport.

4. Conclusions

In this study, three optimization models have been established with different objectives for the inter-regional energy exchange. These models are helpful to identify desired generation plans in terms of economic and environmental efficiency. The following conclusions can be drawn:

(1) The inter-regional energy optimization is mainly achieved by substituting clean energy and high-efficiency large units in the feeding area for small units in the receiving area. Thus, the overall cost would decline, creating more profits.

(2) Clean energy has a large contribution to energy optimization. In light of China's conditions, the UHV transmission lines should fully dispatch wind power in West China when the line security conditions are guaranteed. This would intensify China's economic development and maintain the energy security by enriching the power structure.

(3) Carbon price has a significant role in guiding the inter-regional energy optimization. The trading market of carbon emissions is still in the pilot phase, and the laws and regulations of carbon trading is far from supportive enough. Issues such as the allocation of the initial carbon emission allowance and pricing also need to be addressed. Facing all these challenges, a full consideration should be taken into the guiding role of the carbon price on energy optimization during the development process of the carbon trading mechanisms, which aims to promote the healthy development of China's energy industry with market mechanisms.

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