Analysis Of Regional Carbon Emission Flow Considering Green Power Distribution

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Most existing carbon emission management is based on macro data statistics, representing carbon emissions generated at the production side by static carbon emissions. It is not easy to describe the transfer and apportionment of carbon emissions. This paper studies the relationship between inter-regional power flow and carbon emission flow based on the theory of carbon emission flow of power system. It simplifies the power system in the region, improves the carbon emission flow index, defines the green electricity distribution factor, establishes the regional carbon emission flow calculation method and the carbon emission flow distribution factor analyzes the correlation between the inter-regional carbon emission flow. Finally, taking a Chinese province as an example, the carbon emission flow distribution and green power distribution between provincial municipalities and outward power coupling to other provinces is calculated to verify the method's feasibility. The calculation results clearly describe the carbon emission levels of the regional power systems and the distribution of carbon emission flow in the province and analyze the impact of different power generation structures on the distribution of regional carbon emission flow and the contribution of green power. It provides a reference basis for regional emission reduction planning and new energy site selection.

Keywords: regional carbon emission flow; simplified power system; proportional sharing; carbon emission flow distribution; green power distribution

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1. Introduction.

With global economic development, energy demand in production is increasing, greenhouse gas emissions are significantly increasing, and global climate problems are becoming increasingly severe. To address global climate change, China has solemnly committed to achieving carbon peaking by 2030 and carbon neutrality by 2060. Reducing carbon emissions requires the joint efforts of all industries. As China's most significant carbon-emitting sector, the power industry accounts for over 40% of carbon emissions from fossil fuel combustion. The development of low-carbon electricity is imperative[1–4].

The existing carbon emission calculation in the power industry is based on macro data statistics, which are calculated based on the number of fossil fuels consumed[5, 6]. All carbon emissions generated by power production are attributed to the generation side. However, demand stimulates production, and under the supply-demand relationship, power consumption determines power production, and the load side deserves to take part in the carbon responsibility. The power system carbon emission flow theory couples carbon emissions into power flow [7–9], forming a virtual network flow of carbon emissions, reflecting the transfer of carbon emissions in space, and viewing the carbon emissions generated on the generation side as dependent on power flow as being emitted on the consumption side (load side).

Literature [10]proposed a new method to calculate the carbon footprint of the power grid and obtain the time-varying grid carbon emission factor. Based on the carbon emission flow methodology, National Grid released real-time carbon emission factor data for the UK grid to guide customers on low-carbon electricity use [11]. In order to study the distribution characteristics of carbon emission flow in the power system, the concept of "power system power distribution coefficient" is introduced to relate the carbon emission flow of each node and branch of the power system to the actual carbon emissions of the unit and the carbon emission flow of each part of the whole power system [12]. The carbon emission flow have a strong coupling relationship with the power flow. The carbon emission impact degree is indicated by combining carbon emission flow indicators in evaluating the importance of power system nodes [13]. In the literature [14, 15], the power flow tracking method is used to apportion the power system's grid losses and carbon emissions. The composition of carbon emission sources on the consumption side is clarified, providing a concrete basis for allocating and calculating carbon allowances. Literature [16]proposed a carbon responsibility allocation method based on the theory of carbon emission flow of complex structures to address the problem of unclear carbon responsibility allocation of each link in the low-carbon development of electric power.

Regarding regional carbon emission management, a complex multi-objective model based on probabilistic power flow considering relevant variables is proposed in the literature [17]. This model helps to reduce the total carbon emissions and control the regional carbon emissions. A carbon emission flow tracking method is proposed in the literature [18] for assessing carbon emission levels at the regional and user levels. Coal-fired power generation requires large amounts of coal, which generates another greenhouse gas, methane, during mining and transportation [19, 20]. Literature [21]proposes a multi-flow, multi-node model integrating the coal trade network for power generation and the coal-electricity delivery network to form a spatialized coal-electricity chain. It applies to a case in China to calculate the direct carbon emissions from electricity and coal consumption and the transfer of the implied carbon emissions between regions and the carbon reflows or exchanges in the carbon transfers.

Existing studies on the carbon emission flow of the power system rely on the actual power network topology and calculate the carbon emission flow with the framework of branches and nodes without analyzing it from the region's level. In contrast, the studies on regional carbon emission are conducted from the perspective of carbon emission corresponding to coal consumption, ignoring the characteristics and distribution of the carbon emission shifted along with the transmission of electricity. Aiming at the above problems of the existing studies and in order to better manage regional carbon emissions, the main contributions of this study are as follows:

- Improve the power system carbon emission flow theory, broaden the boundary of using the power system carbon emission flow theory, and establish a regional simplified power system carbon emission flow model to adapt to the carbon emission flow calculation at the regional level.
- Based on the regional carbon emission flow calculation, describe the distribution of carbon emission between regions by distribution factor, and analyze the sources and destinations of carbon emission between regions.
- Define the "Green Power Distribution Factor" to represent the proportion of green power in power transmission and quantitatively describe new energy's contribution to carbon reduction by combining it with the carbon emission flow analysis.

Finally, a province in China is used as an example to calculate the regional carbon emission flow and green power distribution. The results can provide a reference basis for inter-regional low-carbon power dispatch and new energy generation capacity siting.

2. Regional carbon emission flow metrics.

2.1. Regional Simplified Power System Network.

The calculation of regional carbon emission flow is dependent on the power flow. In a region, the structure of its power system is often complex. The carbon emission characteristics vary from region to region with different power generation technologies, which is not conducive to analyzing interregional carbon emission flow. For this reason, regional power systems are simplified [22, 23] to better analyze regional carbon emission flow.

As shown in Fig. 1, each region is a node in the regional simplified power system. If there are power plants in the region, all generating units are equivalent to one unit, and all loads are equivalent to one load. The carbon emission intensity of the equivalent unit is the average carbon emission intensity.

Analyzing regional carbon emission flow requires the definition of several metrics describing regional carbon emission flow based on the theory of power system carbon emission flow[7].

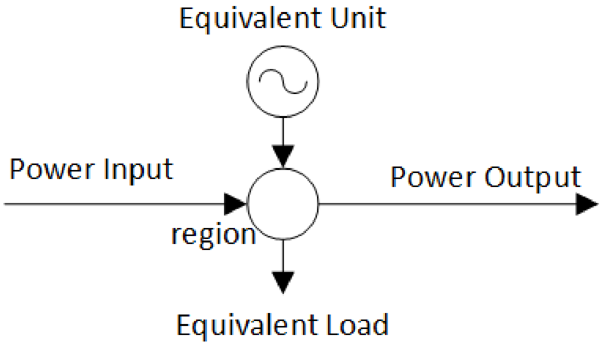

Fig. 1. Regional simplified power system.

2.2. Regional Carbon Emission Flow Quantity.

Regional carbon emission flow quantity is the most basic physical quantity to describe the regional carbon emission flow to characterize the amount of inter-regional carbon emissions and is denoted by the symbol F. In a regional simplified power system network, the carbon emission flow quantity relies on the power flow. The branched carbon emission flow quantity corresponds to the branched power flow, and the nodal carbon emission flow quantity corresponds to the equivalent unit output and load.

For example, the inter-regional carbon emission flow quantity is the cumulative amount of coupled carbon emissions corresponding to the power flow from one region through the power system to another at a given time. Similarly, the mid-region carbon emission flow quantity is the cumulative amount of coupled carbon emissions in power generated by all generators in a region or the cumulative amount of coupled carbon emissions in all loads in a given time.

The regional carbon emission flow quantity unit is the same as the carbon emissions, generally tCO_2 or $kgCO_2$. Regional carbon emission flow quantity is numerically equal to the carbon emissions generated in the generation chain to maintain the operation of generators, inter-regional power flow supply, customer load over a given period.

2.3. Regional carbon emission flow Rate.

The carbon emission flow rate is the carbon emission flow quantity per unit of time, equivalent to the "flow efficiency" concept, and is denoted by the symbol R. In a region, there is a carbon emission flow rate corresponding to the power flow between regions and a carbon emission flow rate corresponding to the region's generator output and customer load. The unit of the regional carbon emission flow rate is generally (tCO_2/h or $kgCO_2$/s). It is numerically equal to the derivative of the regional carbon emission flow quantity concerning time.

$$R = \frac{\mathrm{d}F}{\mathrm{d}t} \tag{1}$$

The regional carbon emission flow quantity is integral to the regional carbon emission flow rate over time.

2.4. Regional Carbon Emission Flow Density.

The power system's energy consumption and carbon emission mainly relate to the active power output, and the reactive power output will affect the active power loss to some extent. However, the overall impact on carbon emissions is minimal. In this paper, the calculation is carried out with the active power without considering the network loss.

Hence, 'Regional carbon emissions are directly related to the active power flow of the power system, and the regional carbon emission flow density is the ratio of the regional carbon emission flow rate R to the active power flow P. Expressed in symbols ρ.

$$\rho = \frac{R}{P} \tag{2}$$

The regional carbon emission flow density describes the carbon emissions per unit of electricity consumed on the power generation side of the electricity transmission between regions, which is the carbon emissions per kW·h. It has a clear physical meaning. According to the definition of regional carbon emission flow quantity and regional carbon emission flow density, the unit of regional carbon emission flow density is the same as the unit of carbon emission intensity on the power generation side, which is generally $kgCO_2/(\mathrm{kW{\cdot}h})$.

The power flow in a region is an instantaneous value. Since the regional emission flow depends on the power flow, the regional carbon emission flow density alsovaries with time. For the convenience of description, the regional average carbon emission flow density in a given period is $\bar{\rho}$.

$$\bar{\rho} = \frac{\int_{T_0}^{T} R\,\mathrm{d}t}{\int_{T_0}^{T} P\,\mathrm{d}t} = \frac{F}{Q} \tag{3}$$

The units of regional average carbon emission flow density are the same as regional carbon emission flow density. Numerically, it is equal to the cumulative regional carbon emission flow rate ratio, i.e., the regional carbon emission flow rate F, to the regional power Q transmitted during this time.

2.5. Regional Carbon Potential

Regional carbon emission flow density describes the relationship between power flow and carbon emission flow between regions. The concept of regional carbon potential describes the relationship between carbon emission flow and power flow in a region. Denoted by the symbol e, the carbon potential of region N is:

$$e_N = \frac{\sum\limits_{i\in\Omega_N^+} P_{l_i}\rho_i + \sum_{i\in\Omega_N^+} P_{G_i}E_i}{\sum\limits_{i\in\Omega_N^+} P_{l_i} + \sum\limits_{i\in\Omega_N^+} P_{G_i}} = \frac{\sum\limits_{i\in\Omega_N^+} R_i}{\sum\limits_{i\in\Omega_N^+} P_i} \tag{4}$$

where: $\Omega_N^+$is the set of all the pathways connected to region N and with power flow intoregion N; P_{l_i} is the active power of the ith pathway flowing into region N; ρ_i is the carbon emission flow density of the ith pathway flowing into region N; P_{G_i} is the output power of the i th unit in region N; E_i is the carbon emission · intensity of the ith unit in region $N\cdot$ When calculating the regional carbon potential, considering the existence of generating units in the region, the unit input power can be equated to the branch input power and expressed uniformly as P_i.R_i is the carbon emission flow rate of the ith pathway flowing into region N. (including the carbon emission flow rate injected by all units).

The regional carbon potential has the same unit as the regional carbon emission flow density, generally $\mathrm{kgCO_2/(kW\cdot h)}$. Suppose there are generating units in the region. In that case, the power generation of the generating units can be considered as the power flow into the region, and the carbon emissions produced by them can be considered as the carbon emission flow into the region.

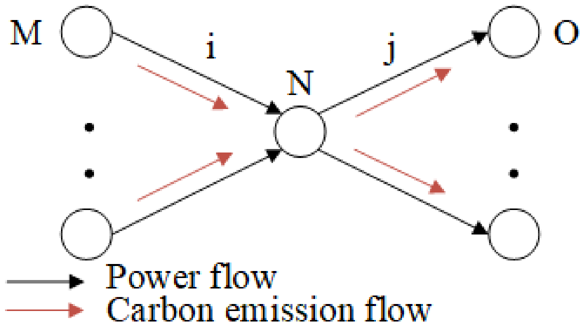

Fig. 2. Inter-regional power flow and carbon emission flow.

Next, the relationship between the regional carbon potential and the density of carbon emission flow into the region is analyzed. Fig. 2 shows a region N with its neighboring regions.

If the set of pathways with power flow injected into region N is Ω_N^+, the set of pathways' with power flow out of region $N\cdot$ is Ω_N^-, and the active power flow injected into region N. from pathway i and out of region N from pathway $j\cdot$ are $P_i\cdot$ and P_j $\left(i \in \Omega_N^+, j \in \Omega_N^-\right)$, respectively. Let pathway j of the outgoing power flow contains the component of pathway i in the incoming power flow as $P_{j,i}$. According to the proportional sharing principle [24, 25], the power flow in any of the pathways in the outgoing region N contains all components of the power flow in the pathway of the inflow region N and satisfies.

$$\frac{P_{j,i}}{P_j} = \frac{P_i}{\sum\limits_{s\in\Omega_N^+} P_s} \tag{5}$$

Let the carbon emission flow density of the active power flow flowing from pathway i $\left(i \in \Omega_N^+\right)$ into region N be ρ_i. The carbon emission flow rate of the active power flow of the jth outflow pathway should be the sum of the contributions of all pathways in N to the carbon emission flow rate of pathway j, i.e.

$$R_j = \sum_{i\in\Omega_N^+} P_{j,i}\rho_i \tag{6}$$

As a result, the carbon emission flow density ρ_{j}' $\left(j \in \Omega_n^-\right)$A of the pathway j is

$$\rho_j' = \frac{R_j}{P_j} = \frac{\sum\limits_{i\in\Omega_N^+} P_{\mathrm{j,i}}\rho_{\mathrm{i}}}{P_j} \tag{7}$$

From Eq. (5), it have

$$P_{j,i} = P_j \frac{P_i}{\sum\limits_{s\in\Omega_N^+} P_s} \tag{8}$$

Substituting Eq. (8) into Eq. (7) and eliminating $P_{j,i}$, then

$$\rho_j' = \frac{\sum\limits_{i\in\Omega_N^+} P_j \frac{P_i}{\sum\limits_{s\in\Omega_N^+} P_s}\rho_i}{P_j} = \frac{\sum\limits_{i\in\Omega_N^+} P_i\rho_i}{\sum\limits_{s\in\Omega_N^+} P_s} = \frac{\sum\limits_{s\in\Omega_N^+} R_s}{\sum\limits_{s\in\Omega_N^+} P_s} = e_N \tag{9}$$

From Eq. (9), it can be seen that under the principle of proportional sharing, the outflow carbon density is a constant independent of the pathway and equal to the carbon potential of the outflow region for all cases where the region also gives all inflow power flow and carbon emission flow density.

2.6. Green Power Distribution Factor.

From the above analysis, it is clear that the magnitude of regional carbon potential depends on the proportion of thermal power and low-carbon power flowing into the region. In order to further analyze the role of green electricity (in this paper, green electricity is zero carbon emission electricity, including photovoltaic, wind power, and hydroelectricity) on regional carbon reduction, the green electricity distribution factor G is defined to characterize the proportion of green electricity in the path of electricity transmission.

$$G_N = \frac{\sum\limits_{i\in\Omega_N^+} P_{l_i}G_i + \sum\limits_{i\in\Omega_N^+} P_{g_i}}{P_{\Sigma N}} \tag{10}$$

where G_N is the green power distribution factor of region N; G_i is the green power distribution factor of the i th pathway flowing into region N; P_{g_i} is the injected active power of the i th green power unit in region N; $P_{\Sigma N}$ is all the active power injected into region N. The green power distribution factor in the region and the pathway, under the principle of proportional sharing, is the same as the relationship between the regional carbon potential and the regional carbon emission flow density, and the proportion of outgoing green power is independent of the pathway and equal to the green power distribution factor of the outgoing region.

2.7. Relationship between the metrics.

Each of the above metrics describes regional carbon emission flows from different perspectives and has a specific mathematical relationship, which can be converted to each other. A comparison of the metrics is shown in Table 1.

3. Regional carbon emission flow correlation analysis.

3.1. Carbon Emission Flow Distribution Characteristics and Distribution Factors.

The distribution of regional carbon emission flow depends mainly on the path and mode of power flow outflow regions to the target region. In order to characterize the carbon emission flow distribution and the correlation between the power flow outflow area and the carbon emission flow distribution, two distribution factors related to the carbon emission flow analysis need to be defined[12].

3.1.1. Regional Output Distribution Factor.

The regional output distribution factor characterizes the proportional relationship between the network flow (either power flow or carbon emission flow) from the starting region to the adjacent target region at a particular moment and the total network flow into that starting region.

Define the regional active output distribution factor H_{ij}^P for region i to region j as

$$H_{ij}^P = \frac{P_{ij}}{P_{\Sigma i}} \tag{11}$$

where: P_{ij} is the active power flow from region i to the adjacent region j; $P_{\Sigma i}$ is the sum of the active power inflows into region i. If the two regions are not connected, or there is no positive power flow into them, $H_{ij}^P = 0$. In particular, when $i = j, H_{ij}^P = 1$.

Similarly, the regional output distribution factor H_{ij}^F of the carbon emission flow is

$$H_{ij}^F = \frac{R_{ij}}{R_{\Sigma i}} \tag{12}$$

where: R_{ij} is the carbon emission flow rate from region i to adjacent region j; $R_{\Sigma i}$ is the total carbon emission flow rate into region i.

If let ρ_{ij} be the carbon emission flow density of the carbon emission flow from region i to region j and e_i be the carbon potential of region i, then by the nature of carbon emission flow, then

$$\frac{H_{ij}^F}{H_{ij}^P} = \frac{\frac{R_{ij}}{R_{\Sigma i}}}{\frac{P_{ij}}{P_{\Sigma i}}} = \frac{R_{ij}}{P_{ij}}\frac{P_{\Sigma i}}{R_{\Sigma i}} = \frac{\rho_{ij}}{e_i} = 1 \tag{13}$$

From Eq. (13), it can be seen that for the same starting and target regions, the carbon emission flow output distribution factor and the power flow output distribution factor are equal. They can be collectively referred to as the regional output distribution factor.

3.1.2. Path Output Distribution Factor.

The path output distribution factor characterizes the contribution of network flows (either active or carbon emission flows) flowing from the starting region through a specific path to the entire network flows flowing into the target region.

Suppose there exists a power flow path l from region i to region j, and the set of branches in this path is $\mathrm{L}(l)$, then the output distribution factor $D_{ij}^{P(l)}$ of this path l from region i to region j is

$$D_{ij}^{P(l)} = \prod_{(r,s)\in \mathrm{L}(l)} H_{rs}^P \tag{14}$$

If there is more than one power flow path from region i to region j, let the set of all power flow paths from region i to region j be Γ. Then the distribution factor D_{ij}^P of the path output from region i to region j is

$$D_{ij}^P = \sum_{l\in\Gamma}\left(\prod_{(r,s)\in \mathrm{L}(l)} H_{rs}^P\right) \tag{15}$$

The path output distribution factor for carbon emission flow and active power flow is determined by calculating it from the regional output distribution factor. Since the derivation process is similar, these factors are proven to be equal, i.e.

$$D_{ij}^F = D_{ij}^P \tag{16}$$

Table 1. Comparison of the metrics.

Metrics	Unit	Meaning	Relationship to other metrics
Regional carbon emission flow quantity	tCO_2 or $kgCO_2$	Quality of CO_2 emissions	From regional carbon flow rate integral
Regional carbon emission flow rate	tCO_2/h or $kgCO_2/s$	Carbon emissions per unit of time	From regional carbon emission flow quantity differential
Regional carbon emission flow density	$kgCO_2/(kW\cdot h)$	Carbon emissions per unit of electricity transmitted across regions	Ratio of carbon flow rate to power in the region of the transmission path
Regional carbon potential	$kgCO_2/(kW\cdot h)$	Carbon emissions per unit of electricity generated in the region	Ratio of carbon flow rate to power in the inflow region
Green power distribution factor	-	Proportion of transmitted electricity that is green in the region	Ratio of green power to total power

D_{ij}^P and D_{ij}^F can be collectively called the path output distribution factor, denoted by the symbol D_{ij}.

The regional output distribution factor represents the ratio of the input power to the total power between two neighboring regions, and the path output distribution factor represents the ratio of the input power of the start region contained in the input power of the end region in a particular path. The path input distribution factor is obtained by multiplying multiple regional output distribution factors.

3.2. Regional Carbon Emission Flow Distribution Mechanism.

For region i, other power outflow regions provide the carbon emission flow into the region at any moment. The contribution of each other power outflow region to the carbon emission flow rate of the region is related to the carbon emission flow injection from other regions and the region's location, which the path distribution factor can characterize. The sum of the carbon emission flow rates into region $i, R_{\Sigma i}$, is

$$R_{\Sigma i}=\sum_{k=1}^{K}P_{Gk}e_{Gk}D_{ki} \tag{17}$$

where P_{Gk} and e_{Gk} are the active output and the regional carbon potential of the kth $(k=1,2,3,\dots,K)$ region, respectively.

From Eq. (17), the component of the carbon emission flow rate into region i from the kth region is

$$R_{G,k-i}=P_{Gk}e_{Gk}D_{ki} \tag{18}$$

From the definition of the regional output distribution factor, the component of the carbon emission flow from region i to region j that comes from the kth region is

$$R_{G,k-(i,j)}=H_{ij}R_{G,k-i} \tag{19}$$

According to the proportional sharing principle, for a region where load exists, the contribution of carbon emission flow injection from all other regions to the carbon emission flow rate of the load in that region is equal to the contribution to the sum of the carbon emission flow rates into that region. If load p_{Li} exists the ith region and the corresponding carbon emission flow rate is R_{Li}, then the component from the kth region in it should be

$$R_{Gk-Li}=R_{G,k-i}\frac{R_{Li}}{R_{\Sigma i}}=R_{G,k-i}\frac{P_{Li}}{P_{\Sigma i}} \tag{20}$$

3.3. Regional Green Power Distribution Mechanism.

Similar to the calculation of carbon emission flow distribution in the previous section, the path distribution factor can characterize the regional green power distribution. The sum of the active power of green power flowing into region $i, P_{g_{\Sigma i}}$, is

$$P_{g_{\Sigma i}}=\sum_{k=1}^{K}P_{Gk}G_{Gk}D_{ki} \tag{21}$$

where: G_{Gk} is the green power distribution factor of the kth region.

From Eq. (21), the component of the green electricity flowing into region i that comes from the kth region is

$$P_{g,k-i}=P_{Gk}G_{Gk}D_{ki} \tag{22}$$

If the load p_{Li} exists in the ith region, then the green component of it from the kth region should be

$$P_{gk-Li}=P_{g,k-i}\frac{P_{Li}}{P_{\Sigma i}} \tag{23}$$

4. Analysis of examples.

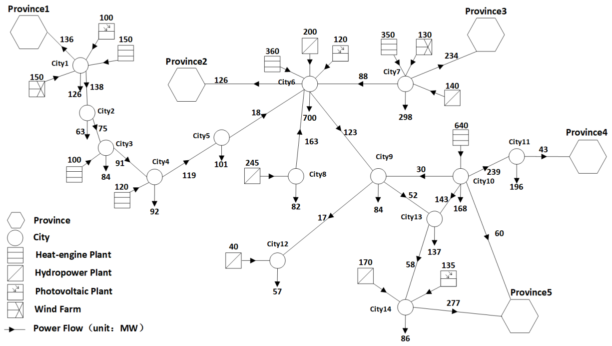

Fig. 3. Inter-regional power transmission distribution in a Chinese province.

In order to visually demonstrate the feasibility of the above regional carbon emission flow calculation, Take a particular province in China as an example for analysis. Figure 3 shows the transmission of electricity between all cities in the province(the relative positions of the regions in the figure do not represent the actual geographical location of the region). The figures in the figure are all the active power in MW at a particular moment. The power characteristics in each city are shown in Table 2. The central and western parts of the province have developed some new energy sources, with more thermal power in the east and more hydropower in the central and southern parts of the province, which are rich in hydropower resources. In this paper, when calculating the regional carbon emission flow, the carbon emission intensity of thermal power is 0.85kgCO_2/(kW·h) [26], and the carbon emission intensity of photovoltaic power, wind power, and hydropower is 0. From this calculation, we get the data related to carbon emission flow.

Table 3 shows the carbon emission flow density among regions, and the regional carbon potential and green power distribution factor are shown in Fig. 4. The regional carbon potential reflects the overall carbon emission level in the region. The green power distribution factor reflects the proportion of green power in the region, and the two show a negative correlation. From Eq. (9), it can be seen that the regional carbon potential determines the density of carbon emission flow from the region to other regions. The western part of the province is rich in renewable resources, and City 1 has more wind power and photo electricity. Hence, the carbon emission flow density on the outflow path of the region is minor. City 2 has no electricity injection, and the regional carbon potential of City 2 is the same as that of City 1. City 3 and 4 have thermal power plants with higher carbon emission intensity. The injection of coal power increases the regional carbon potential of these two cities, and the density of carbon emission flows out from these two regions gradually increases. Cities 6 and 7 have wind power, photovoltaic, and hydroelectric power injection, and the regional carbon potential and carbon emission flow density decrease again. The southern part of the province is rich in water resources. The regional carbon potential of city 8 is 0, and the density of carbon emission flow from city 8 to city 6 is also 0. City 10 has more thermal power plants, which have a lifting effect on the regional carbon potential of the surrounding areas, so the regional carbon potential of City 9, City 11, and City 13, which receive electricity from City 10, is higher.

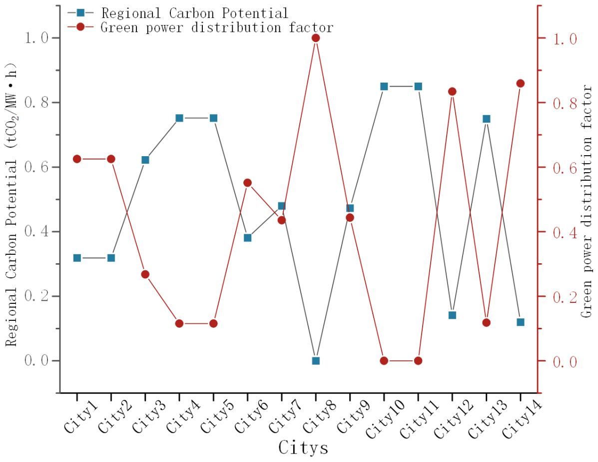

Fig. 4. Regional carbon potential and green power distribution factors in various regions.

The transfer of carbon emissions between regions is represented by Fig. 5, which visualizes the spatial transfer of carbon emissions generated by thermal power generation regions per unit of time in terms of regional carbon emission flow rates. The carbon emission flow calculation depends on the power flow, so its transfer direction is consistent with the power transmission direction. The magnitude of the transmitted power and the carbon emission flow density determines its magnitude. In Fig. 5, City 10 has the most enormous flow of carbon emissions, with a share of 32.1%, and contributes the most to the carbon emissions of the other cities due to the high carbon potential and high power output of the city 10.

Tables 4 and 5 show the calculated carbon emission flow rate contribution of each power outflow region to other regions and the load (regions not listed are zero carbon power outgoing regions, and all contribute zero to the carbon emission flow distribution of other regions). Zero indicates no

Table 2. Power characters for each city (unit:MW).

Cities	Thermal power	Wind power	Photovoltaic	Hydroelectricity
City1	150	150	100	0
City2	0	0	0	0
City3	100	0	0	0
City4	120	0	0	0
City5	0	0	0	0
City6	360	0	120	200
City7	350	130	0	140
City8	0	0	0	245
City9	0	0	0	0
City10	640	0	0	0
City11	0	0	0	0
City12	0	0	0	40
City13	0	0	0	0
City14	0	0	135	170

Table 3. Inter-regional carbon emission flow density.

Outflow Region	Inflow Region	Regional carbon emission flow Density$(tCO_2/MW \cdot h)$
City1	Province1	0.3188
City6	Province2	0.3812
City7	Province3	0.4798
City11	Province4	0.8500
City10	Province5	0.8500
City14	Province5	0.1198
City1	City2	0.3188
City2	City3	0.3188
City3	City4	0.6223
City4	City5	0.7518
City5	City6	0.7518
City7	City6	0.4798
City8	City6	0
City6	City9	0.3812
City10	City9	0.8500
City10	City11	0.8500
City10	City13	0.8500
City9	City13	0.4731
City9	City12	0.4731
City13	City14	0.7495

power exchange between regions. City 8 generates all of its hydroelectric power, so it contributes nothing to the carbon flows of other regions as an area that exports electricity. City 8 is also not affected by carbon emissions from other regions because it is self-sufficient in electricity, so data for City 8 are also not presented in the table. As seen from Table 4, the power flow injected by City 1 flows into most of the cities and has the broadest impact on regional carbon emissions. All thermal power outflow regions deliver some amount of power to cities 9, 12, 13, and 14 and contribute to the carbon emissions of these cities. The closer to the end of the power transmission path, the less the area is affected by carbon emissions from the source, which also reflects in the table. As shown in Table 5, cities 6, 7, and 10 thermal power accounted for a large proportion of the total carbon emissions of the other regions contributed more; the total carbon emissions accounted for 20.9%, 20.3%, and 37.2%, respectively, the sum of the load carbon flow rate of each region is equal to the sum of the carbon flow rate of the injection of each power generation region to satisfy the conservation of carbon emissions flow.

TTables 6 and 7 show each outgoing power region's calculated green power contribution to other regions and loads. Cities 10, 11, and Province 4 do not receive any green power, only thermal power from City 10, and therefore are not listed in the table. All green electricity from city 12 is consumed in the region and does not contribute to other regions. Cities 1, 6, 7, 8, and 14 have sizeable green power

Table 4. Contribution of power output regions to carbon emission flow rate in other regions.

Regions	Contribution of power generation regions to the inflow carbon emission flow **rate of each region** $(\mathrm{tCO_2/h})$					
	City 1	City 3	City 4	City6	City 7	City 10
City 1	127.500	0	0	0	0	0
City 2	43.994	0	0	0	0	0
City 3	23.906	85.000	0	0	0	0
City 4	12.431	44.200	102.000	0	0	0
City 5	7.011	24.928	57.526	0	0	0
City6	1.060	3.771	8.701	306.000	42.226	0
City 7	0	0	0	0	297.500	0
City9	0.137	0.489	1.128	39.661	5.473	25.500
City 10	0	0	0	0	0	544.000
City11	0	0	0	0	0	203.150
City12	0.015	0.054	0.125	4.407	0.608	2.833
City 13	0.047	0.166	0.383	13.479	1.860	130.217
City 14	0.014	0.049	0.114	4.009	0.553	38.731
Province 1	43.350	0	0	0	0	0
Province 2	0.141	0.501	1.155	40.628	5.606	0
Province 3	0	0	0	0	112.282	0
Province 4	0	0	0	0	0	36.550
Province 5	0.011	0.038	0.087	3.059	0.422	80.555

Table 5. Contribution of power output regions to load carbon emission flow in other regions.

Regions	**Contribution of generation area to the carbon emission flow rate of each load** $(\mathrm{tCO_2/h})$						**Total load carbon emission flow rate** $(\mathrm{tCO_2/h})$
	City 1	City 3	City 4	City6	City 7	City 10	
City1	83.513	0	0	0	0	0	83.513
City 2	20.084	0	0	0	0	0	20.084
City 3	11.475	40.800	0	0	0	0	52.275
City 4	5.420	19.272	44.474	0	0	0	69.166
City 5	5.951	21.157	48.825	0	0	0	75.932
City6	0.923	3.282	7.574	266.339	36.753	0	314.871
City 7	0	0	0	0	255.274	0	255.274
City9	0.075	0.268	0.619	21.774	3.005	14.000	39.742
City 10	0	0	0	0	0	193.800	193.800
City11	0	0	0	0	0	203.150	203.150
City 12	0.015	0.054	0.125	4.407	0.608	2.833	8.043
City13	0.033	0.117	0.269	9.470	1.307	91.486	102.681
City14	0.014	0.049	0.114	4.009	0.553	38.731	43.471
Total	127.503	85.000	102.000	306.000	297.500	544.000	1462.003

outputs, accounting for 17.5%, 22.4%, 18.9%, 17.1%, and 21.3%, respectively, and in addition to a portion of them being consumed in the province's proximity, a portion of them is sent to other provinces, which is pivotal to the regional role in reducing carbon emissions.

The above analysis, reflecting the flow of carbon emissions in production and consumption, makes carbon emissions no longer a macro and static concept. Calculating and analyzing regional carbon emission flow can help identify a region with a high carbon emission level and prompt the region to make reasonable low-carbon transformation and optimization. At the same time, the calculation of regional carbon emission flow can also reflect that the high carbon emission level of a particular region is caused by the electricity consumption of other regions, which provides a specific basis for the division of responsibility for emission reduction. Promoting emission reduction in a particular region is no longer the responsibility of a single region but requires the joint efforts of different regions to achieve better. For regions vigorously developing green power, their contribution to regional emission reduction can be quantified by the green power distribution factor, which can facilitate inter-regional green power trading and the introduction of policies related to green power subsidies.

Table 6. Contribution of power output regions to green power in other regions.

Regions	Contribution of power generation regions to the inflow green power of each region (MW)					
	City 1	City 6	City 7	City 8	City 12	City14
City 1	250	0	0	0	0	0
City2	86.250	0	0	0	0	0
City 3	46.875	0	0	0	0	0
City 4	24.375	0	0	0	0	0
City 5	13.747	0	0	0	0	0
City6	2.079	320	38.323	163.000	0	0
City 7	0	0	270	0	0	0
City8	0	0	0	245.000	0	0
City 9	0.270	41.475	4.967	21.126	0	0
City12	0.030	4.608	0.552	2.347	40	0
City13	0.092	14.096	1.688	7.180	0	0
City14	0.027	4.193	0.502	2.136	0	305.000
Province 1	85.000	0	0	0	0	0
Province 2	0.276	0	5.088	21.642	0	0
Province 3	0	0	101.903	0	0	0
Province 5	0.021	3.199	0.383	1.630	0	232.741

Table 7. Contribution of power output regions to load green power in other regions.

Regions	Contribution of generation area to the green power of each load (MW)						Total load green power (MW)
	City1	City6	City 7	City 8	City12	City14	
City1	163.750	0	0	0	0	0	163.750
City 2	39.375	0	0	0	0	0	39.375
City 3	22.500	0	0	0	0	0	22.500
City 4	10.628	0	0	0	0	0	10.628
City 5	11.668	0	0	0	0	0	11.668
City6	1.810	278.525	33.356	141.874	0	0	455.564
City 7	0	0	231.677	0	0	0	231.677
City8	0	0	0	82.000	0	0	82.000
City9	0.148	22.771	2.727	11.599	0	0	37.244
City12	0.030	4.608	0.552	2.347	40	0	47.538
City13	0.064	9.903	1.186	5.045	0	0	16.198
City14	0.027	4.193	0.502	2.136	0	305.000	311.858
Total	250	320	270	245.000	40	305.000	1430

5. Conclusions

This paper establishes a regional carbon emission flow calculation method by drawing on the theory of carbon emission flow of power system and equating the power system in the region. Take a Chinese province as an example which verifies the feasibility of the method and draws the following conclusions from the calculation results:

- Calculating regional carbon emission flow by the equivalence of power systems in a region has the advantages of easy calculation and data visualization. Moreover, analyzing carbon emission flow at the regional level can provide a specific reference basis for emission reduction planning in each region.
- The calculation of regional carbon emission flow clarifies the spatial transfer of carbon emissions and accurately represents each region's carbon emissions level. It is also possible to quantitatively analyze the dilution effect of low-carbon regions on carbon emission flow and the lifting effect of high-carbon regions on carbon emission flow.
- Analyzing inter-regional carbon emission correlation can clarify the sources of carbon emissions in each region, evaluate the contribution of power production regions to carbon emissions in other regions. It has a specific application value for promoting low-carbon development.
- The "Green Power Distribution Factor" defined in this paper enables the tracking of green power from the

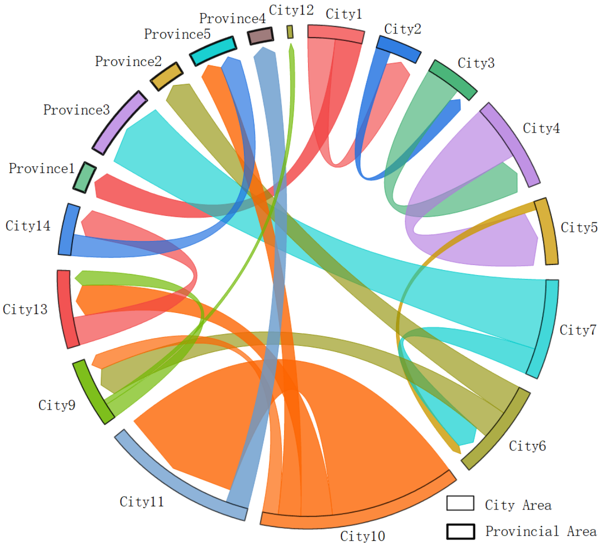

Fig. 5. Inter-regional carbon emissions transfer.

source to load. Combined with the analysis of carbon emission flow, it helps reduce regional emissions from both carbon emission and green power consumption perspectives.

This paper ignores the power loss in the power transmission process when calculating the regional carbon emission flow, which has a particular influence on the distribution of the regional carbon emission flow. The new energy output for some time is treated as constant power output. The actual new energy output is affected by the climate and geographic environment, and the change in its output will also affect the change in regional carbon emission flow. Future work will further consider the impact of complex power and network losses on regional carbon emission flow distribution. The volatility of green power output will be combined with energy storage to calculate regional carbon emission flows at more minor time scales to promote regional low carbon development with "carbon constraint" and "green power constraint."

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