Study on the Effect of Energy Consumption Structure on Carbon Intensity of Hebei Province from the Perspective of Sensitivity

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Abstract. Based on the Kaya identity, the regression equation, involving the carbon intensity, energy consumption structure and energy intensity, is built, then the direct and indirect effect of the energy consumption structure on the carbon intensity is revealed, with the path analysis. Result shows that the shares of coal consumption and primary power are the major driving factors on the reduction of carbon intensity, while the oil consumption ratio, natural gas consumption ratio and energy intensity are the main inhibiting factors of carbon intensity decline. Furthermore, with the carbon intensity sensitivity based on Cobb-Douglas production function and logarithm production function, the carbon emission reduction potential of energy consumption structure optimization is assessed. Result shows that a reduction of one percentage point in the share of coal consumption is substituted completely by the share of oil, gas, primary power consumption, respectively, and the carbon intensity would be reduced by 0.3981 percentage points, 0.4755 percentage points, 0.7476 percentage points, respectively. The reduction of the share of coal consumption will only reduce the carbon intensity by 3.61 percentage points.

1. Introduction
With the coordinated development of Beijing, Tianjin and Hebei becoming the national strategy, Hebei province, as the "ecological environment supporting zone", has put forward the green and low-carbon development as an important breakthrough for its economic transformation. By formulating the 13th five-year plan for energy conservation and the implementation plan for controlling greenhouse gas emissions, Hebei made clear the binding target of energy conservation and emission reduction, which is to reduce the carbon intensity by 20.5 percent by 2020 from that of 2015.

There are many factors contributing to carbon emissions. The researchers mainly employ the Environment Kuznets Curve(EKC) to explore the relationship between economic growth and carbon emissions[1-3]. Economic development usually leads to the increase in energy consumption, thereby increasing carbon emissions. Researchers mainly used co-integration test and granger causality test to reveal the short-term and long-term causality between energy consumption, economic growth and CO₂ emissions. Hwang, Yoo (2014) [4], Rahman, Kashem (2017) [5], Mirza, Kanwal (2017) [6] found that there was a bidirectional causality between energy consumption and CO₂ emissions, that
mean the increase in energy consumption directly affected carbon dioxide emissions, and carbon dioxide emissions would stimulate further energy consumption.

Nevertheless, in the short term, with little room to improve the energy efficiency, reducing the energy consumption is bound to bring down economic growth, thus adjusting the energy structure, namely, increasing the proportion of renewable energy to reduce the dependence on fossil energy, becomes the key point of cutting carbon emissions. Dutta, Champa Bati; Das, Debasish Kumar (2016) [7] used panel data of 30 countries from 1960 and 2010 to analyze the potential impact of relatively clean energy (oil and gas) instead of polluting energy (coal) on a country's economic growth, and found that it would be environmentally beneficial if coal consumption was replaced by oil and natural gas, namely, CO₂ emissions from oil and gas consumption replaced coal consumption.

Hebei province has made clear the goal of energy structure optimization, and whether the energy structure optimization can achieve the goal of the carbon intensity is an urgent question to be answered. So, this paper reveals the correlation among the internal proportion of energy consumption structure, as well as the direct and indirect relationship between energy consumption structure and carbon intensity, then constructs the carbon intensity sensitivity matrix of the energy consumption structure to assess the potential for optimization.

2. Path analysis of the effect of energy consumption structure on carbon intensity

2.1. Model building and data processing

2.1.1. Model building. Based on the Kaya identity, the carbon intensity, namely the ratio of carbon emissions to GDP, can be decomposed as[8]:

\[
D = \frac{C}{Y} = \sum_{i} \frac{C_i}{E_i} \times \frac{E_i}{E} \times \frac{E}{Y} \tag{1}
\]

Thereinto, \(i\) stands for the types of energy consumption. This paper mainly studies the effect of primary energy consumption on carbon intensity (coal, oil, gas, primary power). Therefore, \(i=1,2,3,4\); \(E_i\) stands for the \(i\)th energy consumption; \(C_i\) stands for the carbon emission produced by \(i\)th type energy consumption; \(E\) stands for the total energy consumption; \(Y\) stands for regional GDP. Then, \(C_i/E\) stands for the carbon emission produced by unit \(i\)th type energy consumption, namely, carbon emission coefficient; \(E/E\) stands for the share of \(i\)th type energy consumption in total energy consumption, namely, the energy consumption structure; \(E/Y\) stands for the energy consumption per unit of output, namely, energy intensity.

Assume that carbon emission coefficients of all types of energy consumption are constant, then the carbon intensity mainly depends on the share of coal consumption, oil consumption, gas consumption, primary power consumption and energy intensity, so the model can be expressed as:

\[
Y = \lambda + \alpha_0 I + \sum_{i=1}^{4} \alpha_i ES_i \tag{2}
\]

Thereinto, \(ES_i\) stands for the share of \(i\)th type energy consumption, \(I\) stands for energy intensity, \(\alpha_0\) and \(\alpha_i\) stand for parameters to be estimated, \(\lambda\) stands for stochastic error term.

The path analysis is the further decomposition of Pearson correlation coefficient, which represents the total effect of each independent variable on the dependent variable, including the direct effect of each independent variable on the dependent variable and the indirect effect of each independent variable on dependent variable through other independent variables. That is [9-10]:

\[
r_{my} = p_{my} + \sum_{n} r_{mn} p_{ny} \quad m \neq n \tag{3}
\]

Thereinto, \(r_{my}\) stands for the total effect of independent variable \(X_m\) on dependent variable \(Y\), that is Pearson correlation coefficient between \(X_m\) and \(Y\), and the bigger the absolute value of Pearson correlation coefficient, the bigger the total effect; \(p_{my}\) stands for the direct effect of \(X_m\) on \(Y\), that is the standardized regression coefficient of \(X_m\), namely, direct path coefficient, and the bigger the absolute
value of direct path coefficient, the bigger the direct effect; \( r_{mxn}p_{ny} \) stands for the indirect effect of \( X_m \) on \( Y \) through \( X_n \), namely indirect path coefficient, and \( \sum_{n} r_{mxn}p_{ny} \) stands for the total indirect effect of \( X_m \) on \( Y \).

2.1.2. Data processing. Referring to the basic calculation formula for carbon emission in “2006 IPCC Guidelines for National Greenhouse Gas Inventories”, carbon emissions produced by energy consumption can be expressed as:

\[
C = \sum_{i=1}^{4} E_i f_i \tag{4}
\]

Thereinto, \( C \) stands for carbon emissions produced by primary energy consumption; \( i \) and \( E_i \) mean the same as equation (1); \( f_i \) stands for carbon emission coefficient of the \( i^{th} \) type energy consumption.

So far, many research institutions have calculated various carbon emission coefficients, and as the result of Energy Institute of NDRC is widely applied in China, it is used as the calculation standard in this paper, shown in Table 1.

Table 1. The carbon emission coefficient of primary energy consumption

| Coefficient /tc/tce | coal   | oil     | gas     | primary power |
|---------------------|--------|---------|---------|---------------|
|                     | 0.7476 | 0.5825  | 0.4435  | 0             |

The total energy consumption and its composition, the consumption of coal, oil, gas, primary power, and GDP(strip out the price effect, set 1978=100) are available in Hebei Economic Yearbook - 2016, then the carbon emissions, energy intensity, and carbon intensity can be obtained.

2.2. Results analysis

SPSS16.0 is utilized to conduct the correlation analysis for the variables, and the result, shown in Table 2, indicates that there is a moderate correlation between some variables. So, in order to avoid the influence of multicollinearity brought by Least Squares Method to the regression results, this paper selects ridge regression analysis to fit the above equation (2). Ridge regression analysis gives up partial precision in return for a more realistic significance of regression results, whose effect on dealing with the problem of collinearity is remarkable. The ridge regression method can meet the need of the research because this study does not aim to predict, but to reveal the intrinsic relationship among the variables[11].

Table 2. Result of the correlation analysis(N=36)

|       | \( Y \)   | \( ES_1 \) | \( ES_2 \) | \( ES_3 \) | \( ES_4 \) | \( I \) |
|-------|-----------|-----------|-----------|-----------|-----------|-------|
| \( Y \) | Pearson Correlation | 1        | -0.429   | 0.616     | 0.149     | -0.272 | 1.000 |
|       | Sig. (2-tailed)     | —        | 0.009    | 0.000     | 0.387     | 0.109  | 0.000 |
| \( ES_1 \) | Pearson Correlation | -0.429  | 1        | -0.744    | -0.734    | -0.503 | -0.433 |
|       | Sig. (2-tailed)     | 0.009    | —        | 0.000     | 0.000     | 0.002  | 0.008 |
| \( ES_2 \) | Pearson Correlation | 0.616   | -0.744   | 1         | 0.121     | -0.181 | 0.620 |
|       | Sig. (2-tailed)     | 0.000    | 0.000    | —         | 0.483     | 0.290  | 0.000 |
| \( ES_3 \) | Pearson Correlation | 0.149   | -0.734   | 0.121     | 1         | 0.842  | 0.151 |
|       | Sig. (2-tailed)     | 0.387    | 0.000    | 0.483     | —         | 0.000  | 0.379 |
| \( ES_4 \) | Pearson Correlation | -0.272  | -0.503   | -0.181    | 0.842     | 1      | -0.270 |
|       | Sig. (2-tailed)     | 0.109    | 0.002    | 0.290     | 0.000     | —      | 0.112 |
| \( I \)  | Pearson Correlation | 1.000   | -0.433   | 0.620     | 0.151     | -0.270 | 1     |
|       | Sig. (2-tailed)     | 0.000    | 0.008    | 0.000     | 0.379     | 0.112  | —     |

In use of SPSS16.0, we can make the ridge regression analysis on all the variables, and the ridge
trace figures, including ES1(K), ES2(K), ES3(K), ES4(K), I(K), and the change of determination coefficient determined by different K value are shown in Figure 1 and Figure 2.

![Ridge trace figure of variables](image1.png)

![Determination coefficient -K value](image2.png)

Figure 1. Ridge trace figure of variables  Figure 2. Determination coefficient -K value

As shown in Figure 1, when the value of K reaches around 0.2, parameters tend to be stable. As showed in Figure 2, when the value of K reaches above 0.2, the determination coefficients present a steady decline tendency, rather than a drastic fluctuation. Set K=0.2, then according to the time series data from 1980 to 2015, the normalized ridge regression equation can be expressed as.

\[
\hat{Y} = -0.0444 ES_1 + 0.0767 ES_2 + 0.0855 ES_3 - 0.1276 ES_4 + 0.7382 I \\
(\hat{Y} = -2.9201) \quad (3.4615) \quad (3.2116) \quad (-4.9204) \quad (24.7766)
\]

The coefficient of determination (RSQ) of the equation is 0.9672, and that demonstrates the dependent variable is well explained by the independent variables. At the significance level of 0.01, F=176.7434>F_{0.01}(5,30)=3.70, and the absolute value of t value of the regression coefficient are 2.9201, 3.4615, 3.2116, 4.9204 and 24.7766, respectively, all of which are greater than t_{0.01/2}(30)=2.75. So, the statistical test of ridge regression results is remarkable, and fitting effect of equation is sound.

Based on the above calculation of correlation coefficients and standardized coefficients, according to equation (3), the total effect, direct effect and indirect effect of energy consumption structure on carbon intensity can be obtained in Table 3. Since the ridge regression method has a permissible error, it is reasonable to have a small residual effect. As shown in Table 3, the share of coal consumption and the share of primary power consumption are the main factors to drive the carbon intensity to decrease while the share of oil consumption, the share of gas consumption and energy intensity are the major disincentive factors.

| Independent variable | Total effect | Direct effect | Indirect effect | Residual effect |
|----------------------|--------------|--------------|----------------|----------------|
| ES1                  | -0.429       | -0.044       | -0.063         | -0.320         |
| ES2                  | 0.616        | 0.077        | 0.010          | 0.458          |
| ES3                  | 0.149        | 0.086        | 0.009          | -0.108         |
| ES4                  | -0.272       | -0.128       | 0.014          | -0.199         |

3. Assessment for potential of energy consumption structure optimization on carbon emission reduction
3.1. Construction of carbon intensity sensitivity matrix

Assume that output elasticity of the share of \(i\)th (\(i = 1, 2, 3, 4\)) type energy consumption to the carbon emissions caused by energy consumption and GDP is respectively \(f_i\), \(\gamma_i\), and the substitution elasticity of the share of \(i\)th type energy consumption for the share of \(j\)th (\(j = 1, 2, 3, 4\), and \(i \neq j\)) type energy consumption is \(\gamma_i/\gamma_j\). Then, a reduction of one percentage point in the share of \(i\)th type energy consumption would result in a \(f_i\) percentage points reduction in carbon emissions caused by energy consumption. But in order to keep the output of energy consumption unchanged, it is necessary to increase the share of \(j\)th (\(j = 1, 2, 3, 4\), and \(i \neq j\)) type energy consumption by \(\gamma_i/\gamma_j\) percentage points, which would increase the carbon emission caused by energy consumption by \(f_j\gamma_i/\gamma_j\) percentage points. As a result, with the output of energy consumption being constant, if a reduction of one percentage point in the share of \(i\)th type energy consumption is substituted completely by the share of \(j\)th type energy consumption, the carbon intensity caused by energy consumption would reduce by \((f_i - f_j\gamma_i/\gamma_j)\) percentage points.

3.1.1. Output elasticity of the energy consumption structure to carbon intensity. Equation (4) can be changed into

\[
\frac{C}{E} = \sum_{i=1}^{4} E S_i f_i \tag{6}
\]

Thereinto, \(E\) stands for the total energy consumption, \(C\) stands for carbon emissions caused by primary energy consumption; \(E S_i\) stands for the share of \(i\)th type energy consumption in total energy consumption, i.e. the energy consumption structure; \(f_i\) stands for carbon emission coefficient of the \(i\)th type energy consumption, and can be defined as the output elasticity of the share of \(i\)th type energy consumption to the carbon emissions caused by energy consumption.

Based on the above analysis of carbon emission coefficient of each type energy consumption and the calculation results of the Energy Institute of the National Development and Reform Commission, it is known that the output elasticity of the share of coal, oil, gas, primary power to the carbon emissions caused by energy consumption are 0.7476, 0.5825, 0.4436, 0, respectively.

3.1.2. Output elasticity of the energy consumption structure to GDP. Modern economic growth theory holds that labor, capital, technological progress, resources (energy) are the decisive forces of economic growth. Therefore, the Cobb-Douglas production function with energy consumption can be expressed as[12]

\[
G = AK^\alpha L^\beta E^\gamma \tag{7}
\]

Therefore, \(G\) stands for economic output; \(A, K, L, E\) stand for the input of technological progress, capital, labor, energy, respectively; \(\alpha, \beta, \gamma\) stand for the output elasticity of capital, labor, energy, respectively. Then, considering the contribution of energy consumption structure to energy output, equation (7) can be expressed as[13]:

\[
G = AK^\alpha L^\beta E^{\sum_{i=1}^{4} \gamma_i E S_i} \tag{8}
\]

Take the logarithm, equation (8) can be expressed as:

\[
\ln G = \ln A + \alpha \ln K + \beta \ln L + \left(\sum_{i=1}^{4} \gamma_i E S_i\right) \ln E \tag{9}
\]

According to the characteristics of modern economic growth, the input of labor force, capital and other factors in the current period largely depend on the GDP of the previous period. So, to make specific analysis on the contribution of each type of energy consumption ratio to GDP, the last stage GDP is used to reflect the current input of labor, capital[14], and technological progress is reflected by time variation[9]. Then, equation (9) can be expressed as:

\[
\ln G = \mu + \sigma \ln LG + \rho \ln T + \left(\sum_{i=1}^{4} \gamma_i E S_i\right) \ln E \tag{10}
\]
Thereinto, $G$, $LG$ stand for the current GDP, the last stage GDP, respectively; $T$ stands for the input of technological progress; $ES_i$ stands for the share of $i$th type energy consumption; $\sigma$, $\rho$ stand for parameters to be estimated, $\mu$ stands for stochastic error term.

Then, the output elasticity of energy inputs can be expressed as:

$$
\frac{dG}{dE} = \frac{d \ln G}{d \ln E} = \sum_{i=1}^{4} \gamma_i ES_i
$$

(11)

Since some of the correlation coefficients among different variables are above 0.8, a highly relevant relationship, so in order to avoid the influence of multicollinearity to the regression results, this paper selects ridge regression analysis to fit the above equation.

In use of SPSS16.0, the ridge trace figures, and the change of coefficient of determination determined by different $K$ value are shown in Figure 3 and Figure 4. As shown in Figure 3, when the value of $K$ reaches around 0.2, parameters tend to be stable. As showed in Figure 4, when the value of $K$ reaches above 0.2, the coefficients of determination present a steady declining tendency.

Set $K=0.2$, then the ridge regression equation can be expressed as

$$
\ln G = -1.5668 + 0.3636 \ln LG + 0.2953 \ln T + (0.0054ES_1 + 0.009ES_2 + 0.0088ES_3 + 0.0134ES_4) \ln E
$$

(12)

The coefficient of determination (RSQ) of the equation is 0.9888, indicating that the dependent variable is well explained by the independent variables. At the significance level of 0.01, $F=427.6736>F_{0.01}(5,30)=3.70$, and the absolute value of $t$ value of the regression coefficient are greater than $t_{0.01/2}(29)=2.756$. So, the statistical test of ridge regression results is remarkable, and fitting effect of equation is satisfactory.

According to equation (12), it is known that the output elasticity of the share of coal, oil, gas, primary power to GDP produced by energy consumption are 0.0054, 0.009, 0.0088, 0.0134, respectively.

3.1.3. Carbon intensity sensitivity matrix in Hebei province. According to the basic principle that energy structure influences carbon emission reduction, the sensitivity matrix of carbon emission reduction effect of the energy consumption structure change in Hebei province can be obtained, as shown in Table 4.
Table 4. The carbon intensity sensitivity matrix of the energy consumption structure in Hebei province

|                             | substituted by coal(+1%) | substituted by oil(+1%) | substituted by gas(+1%) | substituted by primary power(+1%) |
|-----------------------------|--------------------------|-------------------------|-------------------------|----------------------------------|
| the share of coal consumption (-1%) | —                        | -0.3981                 | -0.4755                 | -0.7476                          |
| the share of oil consumption (-1%) | 0.6635                   | —                       | -0.1289                 | -0.5825                          |
| the share of gas consumption (-1%) | 0.7748                   | 0.1261                  | —                       | -0.4435                          |
| the share of primary power consumption (-1%) | 1.8552                   | 0.8673                  | 0.6753                  | —                                |

3.2. Assessment for potential based on carbon intensity sensitivity matrix

According to the goal set in “Implementation Plan of the 13th Five-year Plan to Control Greenhouse Gas Emission in Hebei Province”, the carbon intensity of Hebei province will be 20.5% lower in 2020 than in 2015. However, with the share of coal consumption being persistently large, the energy consumption structure in Hebei province is extremely unreasonable, and that was 86.55:7.99:3.30:2.17 in 2015. Besides, based on the main ideas of energy conservation and emission reduction in Hebei province, the adjustment of energy consumption structure should be focused on reducing coal consumption and increasing the share of primary power consumption. Therefore, assuming that the reduction target is solely achieved by reducing the share of coal consumption and raising the share of primary power consumption, according to the sensitivity matrix, in 2020, the share of coal consumption would drop to 59.13%, reduced by 27.42 percentage points, and the share of primary power consumption would rise to 29.59%, which is considered very unrealistic. According to “Energy-saving ‘13th Five-year Plan’ in Hebei Province” and “The 13th Five-year Plan for Renewable Energy Development in Hebei Province”, by 2020, the share of non-fossil energy consumption in Hebei province will reach more than 7%, and that will only reduce the carbon intensity by 3.61 percentage points. So, it is necessary to strengthen the substitution of oil and gas consumption for coal consumption to achieve the goal in carbon reduction. But according to “The 13th Five-year Plan for Gas Development in Hebei Province”, by 2020, the share of gas consumption in Hebei province will reach more than 10%, and that will reduce the carbon intensity by 3.19 percentage points. Then, the conclusion can be that, to achieve the carbon reduction target in Hebei province, we should not only optimize energy consumption structure, but also reduce energy intensity.

4. Conclusion

It is found that the share of coal consumption and the share of primary power consumption have the driving effect on reducing carbon intensity, while the share of oil, gas and energy intensity have the inhibiting effect. So, to further reduce the carbon intensity, it is necessary to promote clean coal technology and improve coal utilization efficiency. Besides, we should accelerate the economic transformation, develop new and high-tech industries vigorously, and reduce the dependence of economic growth on coal consumption.

By the sensitivity analysis of carbon emission reduction effect of energy consumption (ratio), it is known that a reduction of one percentage point in the share of coal consumption is substituted completely by the share of oil, gas, primary power consumption, respectively, and the carbon intensity
caused by energy consumption would be reduced by 0.3981 percentage points, 0.4755 percentage points, 0.7476 percentage points, respectively. Additionally, based on the sensitivity of carbon emission reduction changes in primary energy consumption in Hebei province and the relevant targets of the 13th five-year plan in Hebei province, it is known that the carbon emission reduction target cannot be achieved only by reducing coal consumption (ratio). Energy intensity must be reduced at the same time and a variety of other measures must be taken as well.

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