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Factor substitution and decomposition of carbon intensity in China's heavy industry

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A B S T R A C T

The heavy industry, which accounts for over 60% of China's total primary energy and electricity consumption, has contributed largely to the worsening environmental pollution and CO_2 emissions. This study adopts two-stage estimation based on translog cost function to decompose changes in energy related carbon intensity into substitution effect, technological progress effect, output effect and budget effect. The empirical results show that all the inputs (capital, labor and energy) are substitutes, and the substitution between labor and energy have the highest degree of responsiveness. This is a clear indication that increasing labor inputs in the production process will reduce energy consumption and CO_2 emission while improving the worsening environmental problems in China. Also, the empirical results show that about 45.77% change in carbon intensity is attributable to capital-energy and labor-energy substitutions, which affirms the success of any policy by the government to increase labor and capital inputs at the expense of energy use towards CO_2 mitigation agenda.

1. Introduction

The heavy industry includes all industries that produce production materials and also provides material and technical base for the national economy. According to the definition of *National Bureau of Statistics*, the criteria for classifying heavy and light industries are based on whether the industry produces production or consumption materials. In general, the heavy industry mainly includes the metallurgy, machinery, energy, chemical, building material industries, etc. From the perspective of industrial chain, the heavy industry is an upstream industry, which means that high energy consumption is a major feature of the heavy industry [1].

China's energy consumption, especially fossil energy consumption, has increased rapidly since the reform and opening up in 1978 (Fig. 1). The heavy industry, which is an energy-intensive, plays an important role in the Chinese economy. In 2015, the industry accounts for nearly 65% of China's primary energy consumption and over 60% of electricity consumption. With increasing resource constraints and environment pressures, there is an urgent need to follow a sustainable development path. In this context, energy substitution has attracted increasing attention.

Energy substitution is an important issue in energy economics research, which can be specifically divided into inter-fuel substitution and inter-factor substitution. Inter-fuel substitution is mainly about energy structure optimization, while inter-factor substitution is mainly about the effective allocation of resources, including energy, capital, labor and other input factors of production [2]. Inter-fuel substitution includes developing renewable energy sources, and improving energy efficiency. Inter-factor substitution is mainly to achieve marginal production optimization by adjusting the proportion of other factors, and thus achieving energy savings. In contrast, internal substitution of energy depends on the long-term evolution of technology, while external substitution can be achieved in a relatively short period through the reassignment of input factors.

Fig. 1 shows that fossil energy accounts for a large proportion of China's energy structure. The huge fossil energy consumption has caused high carbon emissions. In 2015, China's CO_2 emission was 9153.9 million tons, accounting for 27.3% of global CO2 emissions. With the increasing attention caused by global warming, the Chinese government is facing pressure on carbon emission reduction,

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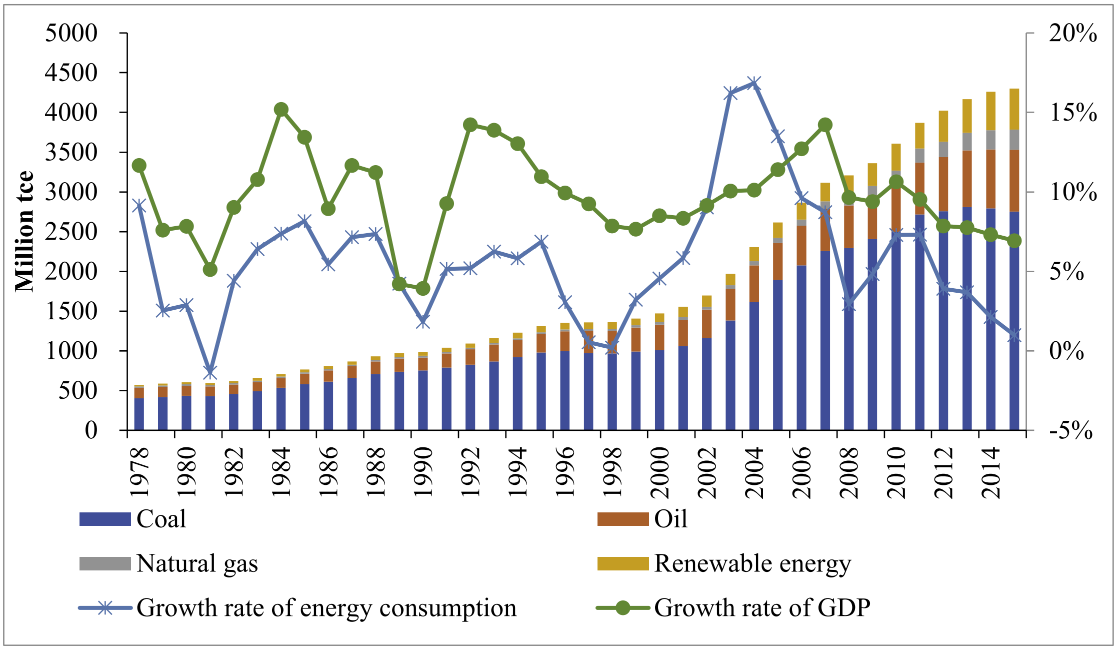

Fig. 1. China's primary energy consumption and the corresponding growth rate in 1978–2015.

and has proposed the goal of reducing carbon intensity by 40%–45% in 2020. In order to achieve this goal, the carbon intensity of the heavy industry needs to be reduced. Hence, the need to examine the main causes of changes in carbon intensity, and analyze the effect of inter-fuel and inter-sector substitutions on the reduction of carbon intensity.

In the existing empirical researches about energy economics, the constant elasticity of substitution (CES) function with the hypothesis of neutral technological progress is mostly used [3–5]. However, it is clear that the CES cannot fully reflect the interaction and relationship between input factors. Therefore, the early studies on energy substitution were mostly carried out with the translog production function (TPF) [6]. TPF is a production function with variable elasticity. However, the TPF assumes that all the input factors for the production function are endogenous, which will lead to conflict when estimating the coefficients with linear regression. This would results in deviation in the substitutable elasticity between energy and other factors [7–11].

Compared with the production function, the translog cost production (TCP) focused more on the perspective of economics rather than technology when analyzing the relationship between input factors and output. Thus, it recognizes the change in output structure, which can help the real substitution between energy and other factors of a given output when energy prices change. For this reason, studies on the substitution between energy and other factors are mostly adapted with the TCP method [12,13].

The concept of substitution elasticity was first proposed by Hicks [14]. Hick's substitution elasticity reflects the relative proportion of input factors changes caused by the change in marginal technical substitution rate. The shortcoming of Hick's elasticity of substitution is that the estimation progress needed to be carried out in the hypothesis that other input factors are not changed. It is obvious that this estimation is biased [15]. improved Hick's substitution elasticity, which has been proven by Ref. [16], and the improved elasticity was named Allen elasticity of substitution (AES). AES is a biased estimation. For example, AES cannot provide the relative proportion of two input factors, and cannot be explained by the marginal substitution rate. Thus, AES cannot adequately explain the substitutable relationship between two factors.

[17] presents the cross-price elasticity (CPE), which reflects the change in another input factor when the price of one factor changes. While the CPE cannot explain the change in the relative proportion of input factors to the change in relative price, (i.e., even if the increase in energy prices led to a reduction in the demand for capital investment) it does not mean that the relative amount of capital investment per unit of product to the energy input per unit of product decreases, while the capital investment per unit of product may increase.

Morishima Alternative Elasticity (MES) proposed by Ref. [18] is a relative replacement rate that can be obtained by the integration of Hicks substitution elasticity and the replacement rate of two or more factors. Through the comparison of MES and CPE, it is possible to estimate not only the response of the proportion of the two input factors to the change in relative price, but also the difference between substitution at the macro and the micro levels. The

Table 1
Comparison of three kinds of substitution elasticities.

Substitution elasticity	Definition	Output	Other input factors $x_k \neq x_i, x_j$	Prices of other factors $p_k \neq p_i, p_j$	Condition of substitutable
CPE	$CPE_{ij} = -\frac{\partial \ln(x_i)}{\partial \ln(p_j)}$	Given	Variable	Given	$CPE_{ij} > 0$
AES	$AES_{ij} = \frac{1}{S_j}\frac{\partial \ln(x_i)}{\partial \ln(p_j)}$	Given	Variable	Given	$AES_{ij} > 0$
MES	$MES_{ij} = \frac{\partial \ln\left(x_i/x_j\right)}{\partial \ln(p_j)}$	Given	Variable	Given	$MES_{ij} > 0$