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Technical efficiency, shadow price of carbon dioxide emissions, and substitutability for energy in the Chinese manufacturing industries

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ABSTRACT

China is the world's largest CO_2 producer and energy consumer. In this paper, we calculate the maximum technically obtainable CO_2 emissions reduction from the efficient use of inputs and estimate the shadow prices of CO_2 emissions in order to assess the potential cost savings deriving from trading emissions among industries by measuring the input distance function for 30 Chinese manufacturing industries. Our empirical results indicate that CO_2 emissions could be reduced by as much as 680 million tons in the aggregate. The shadow prices of CO_2 vary from a high of \$18.82 to a low of zero across industries, with an average of \$3.13 per ton. Additionally, the estimated indirect Morishima elasticities of substitution of capital for fossil fuels indicate that the substitutabilities of capital for oil, gas, and coal are higher than the substitutability for labor.

1. Introduction

China's reform and open policy has helped the country achieve remarkable progress in terms of economic growth and social development since 1979. Over the past three decades (from 1979 to 2009), China's GDP has increased by more than 80-fold, which has resulted in enormous increases in energy consumption, primarily as the result of heavy reliance on energy-intensive industries. Ten years ago, China's total energy consumption was just half that of the United States, but in 2010 China overtook the United States and became the world's largest energy user (China: 2.43 billion TOE; U.S.: 2.29 billion TOE), as is shown in Fig. 1. China's energy consumption is overwhelmingly dominated by fossil fuels, which generate large quantities of carbon dioxide (CO_2). Since China surpassed United States as the largest producer of CO_2 in 2007, China has become the greatest contributor to global warming (China: 8.33 billion tons; U.S.: 6.15 billion tons in 2010), as can be seen in Fig. 1.

Scale-oriented economic development in China has resulted in problems such as resource depletion and environmental pollution. Globally, China is increasingly likely to be obligated to reduce greenhouse gas emissions under the forthcoming post-Kyoto Protocol. China has promoted efforts to improve its performance in terms of environmental protection and energy utilization since 2005. China's 11th Five-Year Economic Plan (2006–2010) clearly illustrates the importance of constructing an energy-efficient and environmentally friendly society.

China's 12th Five-Year Plan (2011–2015), which seeks to establish a “green, low-carbon development concept”, is the first plan to include a commitment to the gradual introduction of market mechanisms for the control of carbon pollution. China has announced several new carbon and energy targets to be fulfilled by 2015 with a benchmark of 2010 levels: increasing the proportion of non-fossil fuels in energy consumption to 11.4%; reducing energy consumption per unit of GDP by 16%; and reducing carbon dioxide emissions per unit of GDP by 17%.

Furthermore, the carbon market mechanism in the 12th Five-Year Plan refers to the establishment of low-carbon product standards, the improvement of the statistical accounting systems for greenhouse gas (GHG) emissions, and the “step by step” introduction of carbon emissions trading markets. The Chinese government has launched initial carbon emissions trading schemes in select pilot regions (Beijing, Chongqing, Shanghai, Tianjin, Hubei and Guangdong), and is planning to construct a unified national system by 2015.

Therefore, it is incumbent on the Chinese government to assess the contribution of efficient use of inputs (including energy) to potential reduction in CO_2 emissions and to investigate how emissions trading systems can best be designed to maximize its cost-effectiveness in connecting buyers and sellers of permits. To accomplish these tasks, in this paper, we calculate the degree of Farrell's (1957) technical efficiency and the shadow prices, or equivalently as the marginal abatement costs, of CO_2 emissions by measuring the input distance function for

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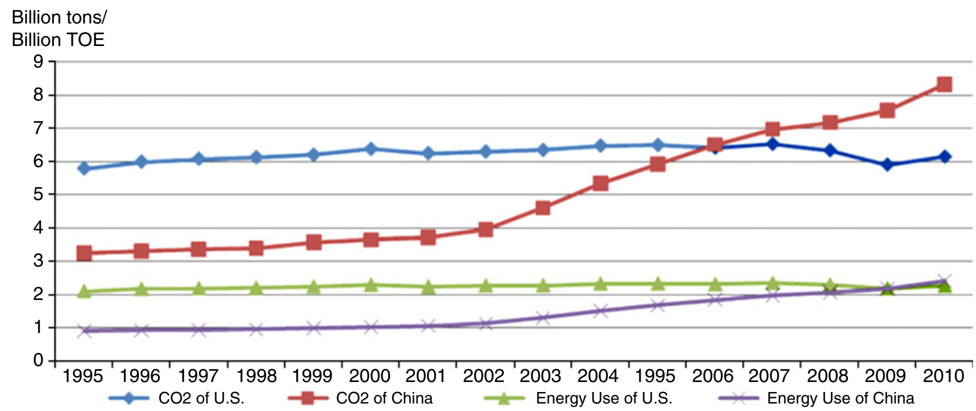

Fig. 1. Comparison of energy use and CO_2 emissions in China and U.S., 1995–2010.

the manufacturing industries that account for 59% of total energy consumption in China, as is shown in Fig. 2.

Some studies researched technical efficiency incorporating CO_2 emissions in different areas. Zhou and Ang (2008) presented several data envelopment analysis (DEA) models to measure economy-wide energy technical efficiency, taking into consideration CO_2 emissions for 21 OECD countries. Zhou et al. (2008) developed several DEA-based technical efficiencies with CO_2 emissions under different production frontiers for eight world regions. Oh (2010) presented a CO_2 emissions-sensitive productivity growth index based on the Malmquist–Luenberger productivity growth index for the technical efficiency analysis of 46 countries. Guo et al. (2011) evaluated the carbon emission performance of 29 Chinese provinces employing DEA. The potential CO_2 emission reductions were computed by promoting energy conservation technology (ECT) and implementing structural adjustment among fossil fuels and non-fossil energy. They estimated total ECT-based potential CO_2 emission reductions at 384.64 million tons for nine technically inefficient provinces in 2007. However, studies of Chinese manufacturing sectors were not incorporated into these literatures.

A few papers attempted to derive the marginal cost of CO_2 emissions abatement for the Chinese provinces. Wang et al. (2011) found that, on average, 28 provinces in China paid $73.10 to abate 1 t of CO_2 emissions in 2007 by utilizing the distance function approach. Wei et al. (in press) estimated the average shadow prices of CO_2 to be $17.60 per ton for 29 Chinese provinces over the 1995–2007 period with DEA. These studies used data arranged by provinces rather than industrial data, presumably because the data for capital stock by industries was not reported (in the *China Statistical Yearbook*) until 2009.[1] Consequently, those papers for China did not attempt to compute the potential cost savings from CO_2 emissions trading across individual industries. However, it is not individual provinces, but rather firms or industries that actually produce output and abate pollution; firm or industry data have been used in most previous literature in which the shadow prices of pollutants are derived on the basis of the distance function.[2]

Additionally, for the first time, we examine herein the degree of substitution of capital for energy (coal, oil, and gas) for the Chinese manufacturing industries subject to environmental regulations; high substitutability (particularly for coal) furthers the objective of "green, low-carbon development". Quality-differentiating coal into quantities of heat, sulfur, and ash, Lee (2005) estimated the indirect Morishima elasticities of substitution among individual inputs for U.S. electric power plants. He found a relatively high substitutability of capital for sulfur.

The remainder of this paper proceeds as follows. Section 2 derives the shadow price of CO_2 and the formula for Morishima elasticity of substitution from the input distance function. Section 3 presents our data and discusses our empirical results, and Section 4 presents our conclusions.

2. The model

In this section, first, we define Shephard's (1970) input distance function and calculate the potential reduction in CO_2 emissions to be obtainable by assuming a technical efficiency of 100%.[3] We assess the substitutability between inputs, especially capital and energy (coal, oil, and gas), by calculating the indirect Morishima elasticity of substitution and derive the shadow price of CO_2, which is equivalent to the marginal abatement of CO_2 emissions.

2.1. The input distance function

Consider a manufacturing firm that produces a vector of outputs $y \in \Re^2_+$ using a vector of inputs $x \in \Re^5_+$. The vector of outputs contains desirable output (q) and undesirable output, CO_2 emissions (u), as a byproduct generated by burning fossil fuels; the vector of inputs comprises two non-energy inputs and three fossil fuels: capital (k), labor (l), coal (c), oil (o), and gas (g). We then define Shephard's (1970) input distance function, which measures the maximum amount by which x can be proportionally reduced while maintaining the level of y:

$$D(y,x) = \sup\{\theta > 0 : (x/\theta) \in I(y)\}, \quad (1)$$

where $I\,(y)$ indicates the input requirement set that can generate y. Note that $D\,(y,x) \geq 1$ if and only if $x \in I\,(y)$. The input distance function satisfies regularity properties: it is monotonically non-decreasing and concave in x, monotonically non-increasing (non-decreasing) and quasi-concave in q (u); it is homogenous of degree one in x (Färe and Grosskopf, 1990; Hailu and Veeman, 2000; Shephard, 1970).

The degree of Farrell (1957)'s technical efficiency (TE) is measured by taking the inverse of the input distance function. If firms operate on the boundary of I (y) (i.e., isoquant), the technically efficient

[1] The data for capital stock (measured as the value of fixed assets) by province is available in the *China Industry Economy Statistical Yearbook*.

[2] Main literature consulted include Färe et al.'s (1993) study of U.S. paper and pulp mills, Coggins and Swinton's (1996) study of U.S. power plants, Hailu and Veeman (2000)'s analyses of the Canadian pulp and paper industry, and Lee (2005)'s examination of U.S. power generators.

[3] Both Shephard and directional distance functions have been used in modeling the technical efficiency of energy use/CO_2 emissions. The directional distance function is theoretically more general than the Shephard distance function, but in some cases the latter might be more suitable. Two recent examples on the use of Shephard distance function to measure energy/CO_2 emission performance are Zhou et al. (2010, 2012a), respectively in a nonparametric and a parametric framework. On the other hand, Zhou et al. (2012b) provides a case where the directional distance function (an extended version) is applicable.