Marginal abatement costs of carbon dioxide emissions and its influencing factors: A global perspective

Jing-Yue Liu, Chao Feng

Business School, Hunan University, Changsha 410082, China
School of Business, Central South University, Changsha 410083, China
Institute of Metal Resources Strategy, Central South University, Changsha 410083, China

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Abstract
Reducing CO2 emissions has become a major and urgent environmental goal worldwide. In this paper, we sample the data of 41 regions (including 165 countries) from 2000 to 2014 and adopt a gravity model to obtain an overview of the global flows of CO2 emissions, energy consumption, the global economy and capital stock since the beginning of the 21st century. We then investigate global technical efficiency, reduction potential, shadow prices and factors influencing the marginal abatement costs of CO2 emissions based on a quadratic directional output distance function. The empirical results show the following: (1) the global centres of gravity for CO2 emissions, energy consumption and capital stock have accelerated their shift to the Asian inland in the 21st century, but the global centre of gravity for the economy did not show the same trend. (2) Global technical inefficiency demonstrates a U-shape, with a turning point in 2007. Average annual total global CO2 emissions could be reduced by 4482.28 Mt, and the global marginal abatement costs of CO2 emissions are approximately 673.74-697.73 USD/t. (3) The relationship between economic development and marginal abatement costs is represented by a U-shaped curve. The world is currently in the climbing phase of this curve, implying that controlling CO2 emissions is becoming more costly. Moreover, energy structure, industrial structure, and CO2 emissions are negatively correlated with marginal abatement costs. Finally, the financial crisis has had a significant effect on marginal abatement costs.

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1. Introduction

In recent years, global warming has become one of the greatest challenges that the world faces, and the primary contributor to this challenge is the continuous increase of greenhouse gas emissions (largely CO2) caused by human activities (Zhang et al., 2014). At present, with the development of the world economy, the total amount of CO2 emissions is increasing: the World Meteorological Organization stated that the global concentration of CO2 in the atmosphere reached 400 ppm in 2015 (Xinhuanet.com, 2016), and exceeded 409 ppm in the spring of 2017, reaching its highest point (Sohu.com, 2017). To prevent global warming, an immediate reduction of CO2 emissions is necessary. However, the reduction of CO2 emissions will consume economic resources and slow economic growth to an unknown extent. Thus, a conflict exists between economic development and environmental protection (Dou, 2015): the difficulties of this battle can be seen in the Kyoto Protocol’s failure to address climatic change and the lack of results from the Copenhagen General Assembly. To coordinate a joint global response to climate change, the United Nations Climate Change Conference in 2015 reached the Paris Agreement, which adopts nationally determined contributions to promote global carbon reduction, thus taking the world a historic step forward in the process of low-carbon energy transformation. However, this historic step remains distant from the target of controlling the temperature increase in this century within 2 °C (Zhou and Wang, 2016).

Under these circumstances, it is both academically and practically valuable to explore paths to achieving low-cost, high-efficiency energy savings to balance the contradiction between energy savings and economic growth. To further promote global energy savings and achieve sustainable development, there are still many tasks to be accomplished. First, the technical efficiency of each
country must be estimated. As a foundation for future work, this step can help us realize the relative ecological efficiency of each country and promote cleaner production. Second, each country must realize its Marginal Abatement Cost (MAC) when promoting carbon reduction. CO₂ is a type of undesirable output in production (Färe et al., 1993); the MAC of reducing this output refers to the loss of any desirable output when reducing each unit of CO₂ under a certain technical level (Zhou et al., 2014). The MAC of CO₂ emissions reflects the opportunity cost for CO₂ emissions abatement and can be used to measure the level of difficulty of CO₂ emissions reductions (Wei et al., 2013). Third, it is very important to determine the reduction potential from improving technical efficiency. Regions or countries with lower costs or greater reduction potential can be considered to be key CO₂ emissions reduction areas. Additionally, research on the global MAC of CO₂ emissions not only provides a basis for making energy saving and emission reduction policies worldwide (Hueting, 1992) but also provides a certain reference value for establishing a global carbon emissions trading market in the future. It is worth mentioning that carbon trading markets do exist; these are mainly conducted at the regional level, and the European Union Emissions Trading Scheme (EU ETS) is currently the world’s largest carbon emissions permit market (Hintermann, 2010). The EU ETS follows the principle of cap and trade, and its main trading products are European Union Allowances (EUAs). The prices of EUAs are mainly driven by the two major allocation methods: free allocation and auctioning. Due to over-allocation and an excessive proportion of free allocations, the prices of EUAs fluctuated violently in the first and second phases of the EU ETS (Madybyura and Andrew, 2011; Zhang and Wei, 2010). Thus, the prices of EUAs are essentially determined by supply and demand and do not reflect the actual price of CO₂ emission reduction, namely, the MAC of CO₂ emissions (Du and Mao, 2015; Wei et al., 2013). Given different levels of economic development, resource endowments and energy consumption structures for each country, how can regional strategies for improving carbon reduction be tailored? What are the main factors influencing the MAC of CO₂ emissions? The answers to these questions are also the targets of this study and are undoubtedly of great importance for global carbon reduction and achieving sustainable development.

An important gap in the current studies is that most of the studies of the MAC of CO₂ emissions have focused on regions and industries while few studies take a global perspective. As is known to all, CO₂ emissions reduction is a global problem, and is related to the sustainable development of humankind and society. It is necessary and important to study the MAC of CO₂ emissions from a global perspective. This paper tries to fill this gap. The main contribution of this study includes three aspects. (1) This paper proposes a parameterized directional output distance function (DFD) for the measurement of technical efficiency and the MAC, which not only conforms to the concept of cleaner production but also ensures the possibility of achieving a “win-win” of CO₂ emissions reduction and economic growth. (2) This paper presents and analyses the historical and current performances in technical efficiency, reduction potential and MAC of CO₂ emissions from a global perspective, which helps us to know how much the global reduction potential of CO₂ emissions is and where the key areas for global CO₂ emissions reduction are. (3) This paper investigates the influencing factors that affect the global MAC of CO₂ emissions for the sake of promoting emission reduction.

2. Literature review

The MAC of pollutants has been attracting an increasing amount of scholarly attention. There are four categories of models used to estimate the MAC of pollutants. The first category is bottom-up models, which primarily include engineering economics models and dynamic optimization models. For example, Van den Bergh and Delarue (2015) investigated the relation between a CO₂ emission cost and CO₂ emission reductions in the power sector based on a bottom-up approach. Simoes et al. (2008) examined the contribution of Portuguese energy policies for MAC of CO₂ emissions based on the optimization model. These models assume that technology is progressing and that there will be more potential room for reducing carbon MACs with the development of technology. Although these models can explain the technical composition of carbon reduction, some studies find that they do not connect with other industrial sectors or consider macroeconomic factors, such as Morris et al. (2012) and Zhang and Folmer (1998). The second category is top-down models, including for example, macroeconomic models (Islam and Grande, 2008), input-output models (Minihan and Wu, 2012) and CGE models (Wang and Dai, 2015). Top-down models focus on linkages between the energy sector and other national economic sectors. However, these models lack a concrete description of energy utilization, and their technical composition is complementary to the bottom-up models. The third category is mixed models, which combine the advantages of bottom-up and top-down models to create a new type of comprehensive model. For example, using the MARKAL-MACRO model, Chen (2005) evaluated the MACs of CO₂ emissions in China and Kumar (2017) estimated the MACs of CO₂ emissions in India. Although mixed models can explain the MAC of pollutants from the perspective of technology and the economy, the model calculation process is complex because two models are joined. The last category is efficiency analysis models, which are newer and more widely used than the other 3 categories; these are primarily used to calculate the shadow price of pollutants to obtain their MAC based on a distance function, such as Pittman (1981, 1983)

Efficiency analysis models can be divided into non-parametric and parametric models according to the different calculation method for distance function. The non-parametric method is primarily used to construct the production possibility set based on Data Envelopment Analysis (DEA) (Zhou et al., 2008). The DEA approach is a data-driven method and has been widely used in production efficiency and the shadow prices of pollutants. For example, Kaneko et al. (2010) calculated the MAC of SO₂ emissions in the thermal power sector in China based on the DEA method. Wang and Feng (2015) analysed the productivity inefficiency in China’s regional economies by applying the DEA method. The main feature of the DEA method is that it is not necessary to construct the functional form. However, when calculating the shadow price based on the DEA method, the not-unique slope of the frontier under efficient observations leads to an uncertain calculated result (Färe et al., 2005; Lee et al., 2002); therefore, the non-parametric method is not well-suited for calculating the shadow price. Moreover, the result calculated by DEA is sensitive to outliers, which may also affect the accuracy of the result (Vardanyan and Noh, 2006; Wei et al., 2013)

Unlike the non-parametric method, the parametric method has a specific functional form for the distance function and then estimates the unknown parameters of this function. According to the different distance functions used, the parametric method can be

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1 Desirable output is one output that is in line with expectations in a production process. Undesirable output is a by-product of desirable output, which is usually harmful to the natural environment and is not conductive to the sustainable development of society (Zhou et al., 2014). Desirable output and undesirable output are produced jointly and together weakly disposable (Du and Mao, 2015; Färe et al., 2005; Molinos-Senante et al., 2015). The relation between desirable output and undesirable output is discussed in more detail in Section 3.2.1.
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