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Optimization on emission permit trading and green technology implementation under cap-and-trade scheme

Wen Yang, Yanchun Pan*, Jianhua Ma, Ming Zhou, Zhimin Chen, Weihua Zhu

Center for Modeling and Optimization of Complex Management Systems (CMOCMS), College of Management, Shenzhen University, Guangdong 518060, PR China

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A B S T R A C T

More and more countries and regions have turned to the cap-and-trade scheme to control carbon emissions. Proper planning of emission permit trading and green technology implementation is beneficial for a generating company to achieve its emission targets at the lowest possible cost. In this paper, a multistage mixed-integer nonlinear programming model is formulated to help make these decisions, which minimizes the total cost of green technology investment, emission permit trading and holding. Differing from previous research, this model captures the characteristics associated with green technology, notably its implementation lasting as a project for several periods and investment cost declining over time due to technology maturation. The holding cost of emission permits as a new operational resource under the cap-and-trade scheme and auto-regression of the carbon price are also considered in the proposed model. The analytical results suggest the optimal trading period and the trading amount of emission permit as well as the starting period for implementing green technology. It is found that the optimal trading period has nothing to do with initial emission permit quota allocated by regulator. In addition, whether or not to invest in green technology is determined by balancing the investment cost and its resulting benefit of reduced emission. Higher carbon price and unit holding cost of emission permit will incent the generating companies implement green technology. The analysis results also illustrate the specific regions in which cleaner/dirtier green technology will be selected or none of them will be considered. Finally, numerical examples validate the analytical results.

1. Introduction

To many scientists it is becoming clear that human activity, especially greenhouse gas emissions produced by energy consumption during production and service, is one of the principal causes of climate change and other global environment problems (Zhang, 2010). One of the responses to reduce greenhouse gas is to implement the Cap-and-Trade (C&T) policy (Du et al., 2016a, b). C&T is a market-based system for controlling carbon emissions by providing economic incentives, with the ultimate goal of reducing the overall emissions in a nation or region (He et al., 2012). Under the C&T scheme, an initial emission quota, which is a permit or allowance of carbon emission during a compliance period (e.g. one year) per generating company, is allocated by government agencies. The emission permit can then be traded among companies in a trading market. This means generating companies can sell surplus or buy additional allowances to vary their amount of emission permits. Companies that cannot control their emission levels will be charged a penalty for their excess emissions which significantly exceeds the 'price' of emission permit (carbon price). Many countries have adopted such emission trading systems. For example, China has initiated pilot C&T systems in seven provinces and cities since 2012.

In order to benefit from emission trading and avoid high penalties from the government, generating companies may resort to implementation of green technology (e.g. adopt more energy-efficient technology) in production processes to reduce their carbon emission levels (Hwang et al., 2013). Most related research concludes that the marginal abasement cost of green technology increases as a function of accumulated emission reduction (Du et al., 2009; Wang et al., 2012; Zhou et al., 2016). For example, the investment in green technology is adopted as a decision variable in Wang et al. (2012), and it is a quadratic function of the

* Corresponding author. 2401 Liberal Arts Building, 3688 Nanhai Ave, Shenzhen, Guangdong 518060, PR China.
E-mail address: panyc@szu.edu.cn (Y. Pan).

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emission reduction. However, in practice, a company usually makes a choice from a finite number of available green technologies associated with various investment costs, implementation periods as well as environmental efficiency factors (Su et al., 2012; Drake et al., 2016; Krass et al., 2013; Nouira et al., 2014). On the other hand, most current research (Debo et al., 2005; Gong and Zhou, 2013; Zhou et al., 2016) assumes that the setup period of a new technology is equal to zero. However, from our survey of some generating companies, i.e. Chuanyi Computer (Shenzhen) Limited Company, Shenzhen Yuhu Power Limited Company, and Shenzhen Pingjin Limited Company, green technology installation/implementation is usually conducted over several periods. For example, a ground-source heat pump system, as an energy saving technology, is a central heating and/or cooling system that transfers heat to or from the ground. The installation of this system normally takes 40–60 days. Consequently, the selection of green technology is actually a "one-zero" discrete decision and the implementation of green technology lasts over multiple periods, which makes the problem more difficult to solve.

In addition, the implementation cost of green technology for the generating company, in reality, usually decreases with the development and maturation of technology (Pan and Kohler, 2007; Niu et al., 2013). From the point of view of the technology supplier, the production cost associated with green technology or equipment will decrease with time. It is because experience can enhance product quality, improve production efficiency, reduce material and labor inputs and thus reduce production cost. Therefore, the investment cost for the generating company to purchase green technology will also decline.

Furthermore, under the C&T scheme, emission permit, like inventory, is one of the firm's most important resources, especially for those large-scale generating companies with high initial emission allowance. For instance, the total emission allowance of Shenzhen Yuhu Power Limited Company is around 0.5 million tons. The money generated by selling permit on the trading market could be used for other purposes. Consequently, the holding cost of emission permit is considered in this paper as an opportunity cost associated with retaining emission permit on hand.

The above issues cause new challenges for generating companies to make decisions on emission trading and green technology implementation. There exist trade-offs between these two decisions. For example, implementation of green technology can reduce purchasing quantity or increase selling quantity of emission permit, and even change emission trading from 'purchase to sell' due to emission reduction obtained from green improvement. In addition, early implementation of green technology will reduce emission level, but will increase investment cost. Purchasing (selling) emission permit earlier (later) will increase opportunity cost of holding emission permit. Proper planning on emission trading and green technology implementation, e.g. when and how much of emission permit should be traded through the trading market, and whether or when to implement green technology, will have significant impact on the performance of generating companies.

To address the foregoing issues, a multistage mixed integer nonlinear programming (MINLP) model is proposed in this paper. The goal of this model is to provide generating companies with effective decisions of emission trading, green technology selection and planning over a compliance period under C&T conditions. The influence of government policy on the implementation of green technology and the impact of autoregressive and fluctuating carbon price and cost of holding emission permit are also analyzed.

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature. Section 3 describes the problem studied and presents our optimization model. The characteristics and the optimal decisions of the model are analyzed and discussed in Section 4. Section 5 provides a numerical study conducted to illustrate the research results. Finally, Section 6 concludes our work.

2. Literature review

There is extensive literature concerning environmental policy since as early as the 1970s (Cropper and Oates, 1992; Fankhauser and Hepburn, 2010; Yi et al., 2011). Most of these articles focused on measurement of carbon emission, allocation of initial emission allowance, qualitative comparison among different policies such as carbon tax and C&T. Some researchers believed that operational decisions had potential impact on carbon emission and there was a need for operations management research to integrate carbon emission concerns (Benjaafar et al., 2013). However, limited research has been dedicated to operational decisions for companies to minimize the impact of environmental policy on their business. Several papers studied lot-sizing problems with carbon emission constraints. For example, Absi et al. (2013) proposed several lot-sizing models integrating carbon emission constraints in four different ways, i.e., on a periodic, cumulative, global or rolling horizon basis. These models helped decide the optimal production period, place and quantity by selecting from multiple supply modes with different supply cost and unit carbon emission. The model with periodic carbon emission constraint was then extended to consider fixed carbon emissions of each mode (Absi et al., 2016). Helmrich et al. (2015) studied a lot-sizing problem with total emission constraint during the planning horizon. The objective of their model was to minimize the total cost including fixed set-up cost, linear production and holding cost, while carbon emission existed in all the processes of set-up, production and storage.

Besides the constrained carbon emission lot-sizing problems, some papers addressed production problems under regulations pertaining to C&T, carbon tax, as well as carbon offsets (Song and Leng, 2012). Chen et al. (2013) investigated economic order quantities under various regulations. They found out that generating companies could reduce carbon emissions without significantly increasing cost by optimizing economic order or production quantities. He et al. (2015) studied the issues of economic production quantity and corresponding optimal carbon emissions under carbon tax and C&T regulations. Unlike Chen et al. (2013), they treated the carbon emission trading prices (purchasing and selling prices) as being different. Zhang and Xu (2013), further, Manikas and Kroes (2015) investigated a newsvendor problem under C&T and carbon tax policies; they derived the optimal production quantity and profit. (Du et al., 2016a, b). built a production optimization model to analyze the influence of carbon footprint and low-carbon preference on the market supply and demand under C&T mechanism. Under C&T and carbon tax regulations, Xu et al. (2016) and He et al. (2017) studied the joint production and pricing problem, and Li et al. (2017) examined the production and transportation outsourcing problems.

Although there is growing literature related to issues of production decisions together with carbon emissions, papers that explicitly consider green technology are relatively few. In terms of green technology selection, Stuart et al. (1999) proposed a product and process selection model with considerations of tradeoff among costs, material consumption, and waste generation. Debo et al. (2005) addressed the problem of technology selection and pricing of remanufacturable products. Krass et al. (2013) analyzed firms' optimal policies of technology selection and maximized social-welfare under different emission regulations. However, these papers did not integrate decision making of emission trading, which is very important under the C&T scheme. As mentioned previously, green technology selection has an impact on emission reduction as