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Environmental resource planning under cap-and-trade: models for optimization

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ABSTRACT

Under the conditions of a Cap-and-Trade (C&T) program, manufacturers are restricted in total greenhouse gas emissions but allowed with options to acquire (and dispose) environmental resource (e.g. certified emission quota (CEQ) or commercialized permit for emission of certain pollutant) via a market system, or conduct self-purification (SP) to reduce emission level to satisfy their overall emission needs due to production or service activities. This paper analyzes the operational decisions of production systems under Cap-and-Trade conditions, in which the problem is modeled as a multi-stage dynamic optimization problem. For each planning period, the model specifically addresses the decisions on purchasing CEQ, reducing emission via SP, and carrying over surplus emission quota (SEQ) to meet the required emission level (driven by production demand) for the period. It also makes sure that the sum of reduced emission over the whole planning horizon meets exactly a goal of emission reduction specified at the manufacturers' discretion. Other important problem characteristics addressed include the unit cost for reducing emission level via SP to reflect the fact that the cost increases as accumulated emission reduction increases, i.e. “the more reduced, the more difficult to reduce”, and time-related cost associated with green investment for emission reduction, e.g. interest cost of short term loans. These characteristics make the model and related analysis useful for both practitioners and researchers in this area. Numerical experiments were designed and carried out to verify and validate the proposed concepts.

1. Introduction

Global warming has been recognized worldwide as a major cause for many negative and significant environmental changes (IPCC, 2007). It is also clear that, based on scientific evidence collected so far, the global warming is caused primarily by unrestricted greenhouse gas emissions often due to over-developed human activities (Zhang et al., 2011). To effectively reduce the greenhouse gas emissions (i.e. carbon dioxide equivalent or CO_2-e emission), many mechanisms have been developed. Among which Cap-and-Trade (C&T) is regarded as one of the widely implemented programs based on eco-economic theory (Dales, 1968). Known as emissions trading, C&T is a market-based policy for controlling CO_2-e emission. Under a C&T program, manufacturers or “emission generating companies” in a region are allocated emission allowances to offset their pollutant emission. Initial allowance can be grandfathered or auctioned through a regulatory agency, and then be traded later among the generating companies through market transactions (EPA, 2012). The total of emission allowances issued is restricted by a pre-determined cap, which is gradually tightened over time. Well established C&T systems around the world include European Union Emissions Trading System (EU-ETS), CRC Energy Efficiency Scheme UK (CRC), Western Climate Initiative (WCI), and Tokyo Cap and Trade (TMG). In China, the government has committed to cut its CO_2-e emission per unit of gross domestic product (GDP) by 40%–45% of 2005 level by 2020 (Yi et al., 2011), and is aggressively pushing for a compulsory carbon emission reduction program based primarily on administrative penalty and market trade of emission allowances (EN, 2010). Shenzhen was chosen as one of the earliest seven experimental cities in China

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where a C&T program is being established and some empirical studies have been done for this research (Shenzhen Emission Exchange, 2012).

It is evident that industrial systems behave significantly different under the conditions of Cap-and-Trade program (Lu et al., 2013). In addition to traditional production resource (e.g. labor, equipment and raw materials), manufacturers now have to consider the acquisition and disposition of environmental resource, that is, emission allowance or commercialized permit for emission of certain pollutant, and balance goals between production economy and green improvement. Decision makers face greater challenge in production and resource planning under C&T conditions. In addition to traditional production resource planning, they now have to plan and acquire environmental resource (e.g. maintaining enough CO_2-e emission quota) to meet the goals of production, which unfortunately causes CO_2-e emission. Given the production requirements over the periods of a planning horizon, the emission needs corresponding to each period can also be estimated. Decision makers need to choose from purchasing certified emission quota (CEQ), or reducing emission level via self-purification (SP), or carrying over surplus emission quota (SEQ) to meet the required emission (caused by production requirement) for the planning period. In this paper, self-purification is defined as a process conducted autonomously by a generating company to reduce its total CO_2-e emission due to production/service operations through the improvement of product design and/or processing methods or process technologies. Klemes (2013) shows many useful and advanced technologies such as total site, process-based graphical approach, and so on, to reduce the energy consumption (e.g. heat and water) and emissions. Observations have revealed following characteristics in this decision-making process: (1) market price of CEQ follows a random fluctuation (Wei et al., 2010); (2) the cost of performing SP to reduce emission level increases as the accumulated reduction increases, i.e. the more reduced, the more difficult to reduce (Du et al., 2009); and (3) many enterprises borrow short-term loans for technological innovation such as green improvement and the interest payment (a function of time and fluctuating interest rate) can be significant. When these characteristics couple together, they may cause significant trade-offs between decision alternatives. For instance, purchasing more carbon credits via market trade might be a better option than reducing emission level via SP when the market price of CEQ is low; likewise, it might be more cost efficient to reduce emission level by a large amount in a single period and carry it over (to satisfy over-emission needs) for several consecutive periods than spreading the reduction over the periods. These trade-offs can lead to significant cost-savings. Consequently it is important for managers to decide how to satisfy the emission needs across the planning periods via different options available under the conditions of C&T. This paper focuses on the decision options of purchasing CEQ or performing SP to reduce emission level, the two most commonly used strategies in practice (Zhou et al., 2013).

Since last two decades, many studies have focused on the issues related to allocating initial emission allowance to generating companies (James and Chen, 2012), especially in China (Wang et al., 2013), and the design of mechanism for carbon-credit trade (Christos and Woodland, 2013). Zhang and Wei (2010) reported an excellent overview about the similar research on the EU-ETS. He et al. (2012) compared C&T mechanism versus carbon taxes. The unique characteristics of emission reduction under C&T program and its impact on production operations have also drawn a great attention. For instance Chen et al. (2013) proposed an economic ordering quantity (EOQ) model with emission constraint considered. They studied relationship between emission allowance, carbon price, carbon emission and total operational cost with the assumption of deterministic demand and analyzed the trade-off condition between carbon emission and inventory cost. Bouchery et al. (2012) introduced sustainability objectives into classic single-stage EOQ model and analyzed the characteristics of optimums under the condition of deterministic demand. Considering multi-stage trade of emission permit, Rong and Lahdelma (2007) proposed a multi-stage stochastic optimization model to make planning decisions on heat and electric energy for an energy company. System simulation was employed in their model to obtain the optimal combination of production quantity. To solve the short-term scheduling of thermal units problem with energy cost and emission constraint considered, Catalao et al. (2008) proposed a multi-objective nonlinear optimization model, which derived a Pareto-optimal solution set of energy cost and carbon emission via a ε-constraining method. Absi et al. (2010) modeled a kind of carbon-constrained lot-sizing problem and achieved the optimum solution in which customer demand was deterministic and the case was in a small-scale.

In addition, some researchers focused on resource selection and allocation for enterprise with emission reduction considered. By introducing the trading cost of emission allowance into operational cost function and constraint condition, Kockar et al. (2009) proposed a single-stage linear programming model to study the influence of emissions trading scheme on generation scheduling of power plant and balance between purchasing emission permit and paying regulation penalty. Aiming at a target of emission reduction, Wang et al. (2012) proposed a stochastic programming model to analyze three possible pathways of green improvement, i.e. using emission-reduction equipment, developing emission-reduction technology, and changing energy input structure. They used a Lagrange function to derive optimal solution of investment. Chang et al. (2012) introduced environmental factors into the optimization process of a municipal solid waste management system. Multiple objectives such as maximizing total revenue and minimizing environment pollution (CO_2-e emission as the measurement standard) were considered in their linear and integer programming models. Zhang and Xu (2013) studied a multi-item production planning problem with C&T mechanism, in which a firm used a common capacity and carbon emission quota to produce multiple products for fulfilling independent stochastic demands. A profit-maximization model was proposed to analyze the optimal policy of production and carbon trading decisions for a single-stage problem and no self-purification process was included. Andrew and James (2015) proposed a newsvendor model to solve the production planning and emission trading problem with time cost of holding emission allowance considered under cap-and-trade scheme. However, self-purification was not included in their model as an option for offsetting carbon emission. Taking the carbon footprint and low-carbon preference into consideration, Du et al. (2016) presented a model to help emission-dependent manufacturer optimize production quantity and emission trading decisions under C&T scheme in which only one single-period situation was considered and the time cost of investment for green improvement excluded. These studies revealed that C&T conditions generate significant impact on the resource selection and allocation of enterprise, and analytical models can be effective in identifying decision trade-offs that often lead to optimal solutions. A comprehensive analytical framework that integrated more renewables to achieve energy self-sufficiency was proposed by Vujanovic et al. (2015), in which multi-objective mixed-integer linear programming synthesis was applied on a dynamic supply network to obtain optimal solutions.

While the literature seems abundant, there is clearly a lack of research to address the following issues or important problem