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Self-scheduling of a power generating company: Carbon tax considerations

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ABSTRACT

The Carbon Tax Self-Scheduling (CTSS) model for a power generating company (GENCO) is proposed in light of the deregulated electricity market environment. The model analyses the effects of GENCO profits and emissions profiles under different carbon tax scenarios, by valuing the specific part of the cost which affects the environment. The resolution method provides first a Mixed Integer Quadratic Programming (MIQP) formulation of the CTSS problem. Second, using piece-wise linearisation approximation methods, the MIQP formulation is transformed into a Mixed Integer Linear Programming (MILP) system. Simulation results of 10–100 unit systems over 24 h show that the MILP formulation is efficient and precise when calculating problems of such a large scale. We conclude that the increase of carbon tax reduces carbon emissions and the reduction effect is more favorable in the case of relatively modest carbon tax. The profit of GENCO is unnecessarily negatively related to the carbon tax, while it is determined by the increased rate of electricity price. The increase of carbon tax may inhibit demand. However, the inhibiting effect may be weakened when considering increases in electricity prices combined with the carbon tax.

1. Introduction

Global warming refers to the observed century-scale rise in the average temperature of the Earth's climate system and its related effects. In recent years, the effects of global warming have drawn more and more global attention [1]. Most of global warming was being caused by increasing concentrations of greenhouse gases. To deal with the impacts of greenhouse gases emissions, especially carbon dioxide, some countries have introduced an efficient economic measure—a carbon tax—in order to save energy and reduce carbon dioxide emissions [2]. The Netherlands, Denmark, and Sweden have been collecting carbon taxes for more than 10 years. China has also listed such a scheme into its national development program, and would begin to collect the carbon tax as early as the 13th five-year plan period (2016–2020) [3]. Fossil fuel burning is response of the major amount of the increase in CO_2 emissions. The amount of global CO_2 emissions in 2011 from fossil fuel combustion was 34.8 billion tonnes. Coal burning was responsible for 43% of the total emissions [4]. Since the power sector discharges significant quantities of carbon dioxide, the creation of a carbon tax brings new challenges to production processes. Meanwhile, the carbon tax provides new developments to traditional problems in power systems, such as the scheduling of a power generation company (GENCO).

Typically, a GENCO is a commercialized entity under independent management and operation. In the competitive electricity markets, a GENCO is responsible for estimating the future electricity price trend by using electricity price prediction model [5]. A given GENCO optimizes its unit generation at each period of time, and formulates the optimal generation bidding plan, thus maximizing profits. In presence of carbon costs, energy savings and emissions reduction policies, what is new for the GENCO is to consider the generation and pollution costs in the above model together with the optimization of its generation strategy.

In previous literature [6] dedicated to electricity prices fluctuations, the unit generation optimization model for different time periods within a trading day has been established so as to consider: the actual bidding risk coefficient, environmental protection costs, unit operation costs, and valve point effects. In other scholar works [7], a unit composite pattern coordinating the electricity market and energy savings scheduling has been designed, by using the emissions load functions of CO_2 (instead of its energy consumption counterpart). By introducing weighting factors, other studies report [8] weighted GENCO's profits,

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generation costs, and emissions in order to establish a self-scheduling model. Last but not least [9], a multi-objective GENCO self-scheduling has been proposed by simultaneously applying the generating profit and pollution emissions as objective functions.

The self-scheduling models of GENCO, considering the limitations of emissions, describe the influences of the environment on generation self-scheduling to some extent. However, with the extensive application of economic theory to the area of environmental management, the carbon tax may be seen as the least cost regulatory tool to achieve binding emissions reduction objectives [10–15]. In Europe, [10] point that a carbon tax is effective in reducing emissions only in the case of high tax rates. In the case of Japan, [11] also find that high tax rates reduce carbon emissions. In China, [12] analyze the effects of three carbon tax rates (high, medium, and low) on emissions reduction and related influences on the macroeconomy and industrial sectors using the Computable General Equilibrium (CGE) model. The simulation suggests that carbon tax can reduce the CO_2 emission effectively, amounting to 11.41 and 21.32 million tons abatement with high tax rate. In China, [13] show that nearly 3% reduction in CO_2 emissions from the 2010 level can be achieved by levying a carbon tax at 50 Yuan/tonne. In the case of South Africa, [14] indicate that a phased-in carbon tax of US$30 per ton of CO_2 can achieve national emissions reductions targets set for 2025. In the case of Australia, [15] employ a CGE model with an environmentally extended Social accounting matrix. According to the simulation results, the A$23 carbon price achieves less than half of the emission reduction target. The gap would have to be made up by purchases of permits from international markets.

Recently, carbon emissions have been paid more attention in energy sector [16–18]. In the case of Scotland, [16] find that by imposing a tax £50 per tonne of CO_2 the 37% CO_2 reduction is met by the year of 2020. There are huge reductions in emissions in energy sectors, emissions in the coal and coal electricity generation sectors fall by 70% and 79% respectively. In China, [17] indicate that a moderate carbon tax would significantly reduce carbon emissions and fossil fuel energy consumption. Of the fossil fuels in use, reducing coal consumption would have the greatest impact on reducing carbon emissions. In the cases of Irish and Portuguese electricity supply system, [18] show that when CO_2 prices stay below 50 €/tonne by 2050 there is no reduction in emitted CO_2 emissions when compared to the levels of 1990. For CO_2 prices reaching between 50 and 100 €/tonne there is a clear reduction in CO_2 with the increase in the price, from 7% with 50 €/tonne to 79% with 100 €/tonne. For prices above 100 €/tonne the increased taxation has only a slight impact on the reduction of CO_2 emissions.

Overall, most of the above-mentioned studies conducted their analysis from an aggregated and long-term perspective. In this study, we will investigate the impact of a potential carbon tax on emission reduction, from a microeconomic perspective of a profit maximizing entity. The central contribution of this paper is that carbon tax can result in emission reduction, even if private, profit maximizing entities apply short-term, price taking, profit maximizing strategies. Certain tax levels can even result in emission reduction, alongside wealth increase.

In the remainder of the paper, Section 2 introduces the CTSS model. Section 3 provides MIQP and MILP solutions. Section 4 contains the simulation results. Section 5 briefly concludes.

2. The carbon tax self-scheduling (CTSS) model

This section details the objective function and the constraints conditions entering the formulation of the CTSS problem.

2.1. The objective function

GENCOs focus on how to achieve the maximum profit by arranging the optimal scheduling of generation units according to their predictions on demand and the electricity price at different time periods in the premise of meeting the restrictions for running of generating units. The CTSS model of a typical GENCO takes into account the influence of the carbon tax, and optimizes the scheduling of generating units, so as to maximize profits. The profit of GENCO refers to the difference between the generating income and costs. The generating income is obtained by selling power in the electricity market. With the introduction of the carbon tax, the generating costs are equal to the sum of fuel costs, start-up costs and carbon emissions costs needed by power generation. Therefore, the CTSS objective function includes three parts: the first part is the generating income; the second part is constituted by fuel costs and start-up costs of generation units; the third part is the emissions cost, as written in Eqs. (1)–(4).

$$\max \ F = R_V - T_C - E_C \tag{1}$$

$$R_V = \sum_{t=1}^{T} \sum_{i=1}^{N} \lambda^t u_i^t P_i^t \tag{2}$$

$$T_C = \sum_{t=1}^{T} \sum_{i=1}^{N} [u_i^t f_i(P_i^t) + u_i^t (1-u_i^t) C_{Ui}^t] \tag{3}$$

$$E_C = \sum_{t=1}^{T} \sum_{i=1}^{N} E_{tax} u_i^t g_i(P_i^t) \tag{4}$$

where F is the profit; R_V represents generation income; T_C is the total fuel and start-up cost combined; E_C is the emissions cost; T refers to the total time period; N is the number of generation units; λ^t represents the electricity price in time period t; and u_i^t is the operation status of unit i during period t. When $u_i^t = 1$, it implies that unit i is in operation, and when $u_i^t = 0$, it is stopped. P_i^t, $f_i(P_i^t)$, and C_{Ui}^t refer to the active generation, fuel cost function, and start-up costs of unit i at time t, respectively; E_{tax} represents the carbon tax, and $g_i(P_i^t)$ is the characteristic emissions function of unit i at time t.

Eq. (2) describes the generating income of N generation units of GENCO at the scheduling horizon T. It sums the products of the active power output of generation unit i at time period t, and the electricity price [19].

Eq. (3) represents the generation cost of N generation units of GENCO at the scheduling horizon T. It includes the fuel costs and start-up costs of generation units. The fuel cost $f_i(P_i^t)$ of generation unit i at time t can be expressed by resorting to the following quadratic function [20]

$$f_i(P_i^t) = \alpha_i + \beta_i P_i^t + \gamma_i (P_i^t)^2$$

where $\alpha_i, \beta_i, \gamma_i$ are parameters of the unit i.

The start-up costs C_{Ui}^t in Eq. (3) refer to costs produced by generation unit in the conversion process from outage state (i.e., do not generate power) to operational state (i.e. generate power), specified as [21]

$$C_{Ui}^t = \begin{cases} C_i^{hot} : & \underline{T}_i^{off} \le -T_i^t \le \underline{T}_i^{off} + T_i^{cold} \\ C_i^{cold} : & -T_i^t > \underline{T}_i^{off} + T_i^{cold} \end{cases}$$

where C_i^{hot} is the warm start-up cost of unit i; C_i^{cold} refers to its cold start-up cost; $\underline{T}_i^{off}$ is its minimum down time, T_i^t is its consistent operating time (positive) or stop time (negative) in period t, and T_i^{cold} is the cold start-up time.

Eq. (4) refers to the carbon emissions cost of N generation units of GENCO at the scheduling horizon T. It sums the products of the