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Planning carbon dioxide mitigation of Qingdao's electric power systems under dual uncertainties

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A B S T R A C T

Coupling with rapid economic development and continual urban expansion, CO_2 as the dominant contributor to the greenhouse has aggravated the global climate change, such that achieving the joint goal of increasing electricity demand and mitigating CO_2 emission become crucial to plan electric power systems (EPS). Various complexities and uncertainties exist in the real-world EPS problems, which can affect the optimization processes as well as the generated decision schemes. In this study, a two-stage interval-possibilistic programming (TIPP) method is developed for planning carbon emission trading (CET) in the EPS of Qingdao (China), where dual uncertainties expressed as interval-random variables and interval-possibilistic parameters can be handled. Techniques of support vector regression (SVR) and Monte Carlo simulation are used for predicting electricity demand and CO_2 emission. Four scenarios corresponding to different CO_2-emission permits and CO_2-mitigation levels have been analyzed. Results reveal that coal-fired power is the primary CO_2-emission emitter, and it tends to the transition to renewable energy-dominated power with the CO_2-mitigation levels from 5% to 30% (e.g., contributing to 0.6% increment of renewable energies and [30.8, 33.1] % reduction of treated CO_2 emissions). Compared to without CET scheme, CO_2 emissions can be reduced about 5% under the CET, demonstrating that CET can help to promote the cleaner production of the local electricity. The findings can help decision makers reallocate carbon permits among different emitters effectively, provide appropriate mitigation plan for CO_2-emission, as well as to improve environmental and sustainable EPS planning.

1. Introduction

Coupling with rapid economic development and continual urban expansion, CO_2 as the dominant contributor to the greenhouse has aggravated the global climate change which including Himalayan glacier melting, desertification, water pollution, geological disasters, frequent collapses, and other industrial accidents (Monkelbaan, 2014). According to the International Energy Agency (IEA), global emissions of carbon dioxide stood at 32.3 billion tonnes in 2014, and the global demand for coal over the next five years would continue marching higher, breaking 9-billion-tonne level by 2019 (IEA, 2015). IPCC estimates suggest that if current emission trajectories continue, it will be impossible to keep the rise in global average surface temperatures to 2 °C above pre-industrial levels (IPCC, 2014). According to China Statistical Yearbook, the national CO_2 emissions reached 11.50 billion tons in 2014, China will continue facing enormous domestic pressures to control its carbon emissions and international pressures to commit to a mandatory carbon emissions target (Xu and Lin, 2016). Because of the continuing increasing electricity demand, investigating the influencing factors of CO_2-emission in China's main industrial sector is of vital importance (Shao et al., 2016).

China's manufacturing industry is the largest energy consumer and carbon dioxide emitter due to the low technology level (Xie et al., 2016). The industry accounts for nearly 60% of China's total energy consumption and over 50% of total CO_2 emissions. In China, coal plays the dominate role in its energy consumption (i.e. exceeding 65%), of which 50% coal consumptions are ascribed to the power industry. Approximately 80% electricity is generated from

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coal-fired power plants, which leads to the coal becoming the main factor to carbon emission (Yang and Lin, 2016). In order to achieve a low-carbon economy lifestyle, Chinese government has implemented several regulations on energy conservation and carbon emissions control since 2006, and invested US$56 billion in developing clean energies in 2013 (UNEP, 2014a; Wang et al., 2015). In 2014 APEC Leaders' Summit, Chinese government announced a goal that, by the end of year 2030, China's non-fossil energy will account for 20% of the primary energy sources (APEC, 2014; GA, 2014). Therefore, increasing electricity demand as well as mitigating CO_2 emission continues to be challenges faced by the managers in public and private sectors. In responses to these concerns, decisions with sound economic and environmental efficiencies are desired to effectively planning electric power systems (EPS).

Previously, a number of research efforts were conducted for mitigating CO_2-emission such as carbon tax, carbon capture techniques, clean development mechanism (CDM) and carbon emission trading (CET) as well as new managerial systems (Chiarini, 2014; Dormady, 2014; Park et al., 2014; Lam et al., 2015; Murray and Rivers, 2015; Charitou, 2015; Fan et al., 2016; Ortas and Álvarez, 2016; Purohit et al., 2016). In detail, carbon tax was proposed as a price instrument to reduce CO_2 emissions by imposing an extra cost on emitters (Murray and Rivers, 2015; Chiu et al., 2015). Carbon capture techniques were used to capture CO_2 emitted from power plants during electricity generation process (Petrescu and Cormos, 2015; Sharma et al., 2016; Liu et al., 2016; Nwaoha et al., 2016). CDM were used for stimulating the development of renewable energy sources such as wind power, solar power, biomass power and nuclear power (Hieronymi and Schüller, 2015; Murata et al., 2016). Managerial systems (e.g., ISO 14001 certification, CSR and even lean combined with green) were aimed at planning a company's operational and administrative activities for managing its environmental aspects and processes (Oliveria et al., 2016; Arimura et al., 2016; Habek and Wolniak, 2016). Among them, CET as a quantity instrument is a governmental policy-driven tool and tends to control emissions in a flexible way through market mechanisms rather than through compulsory regulation, which can effectively stimulate technology innovation for carbon mitigation and can provide cost-effective and flexible environmental compliance for EPS (Zhu et al., 2015).

Although these studies were effective for planning CET with a cost-effective way, most of them conducted deterministic analyses at a macroscopic level, which could incapable of handling complexities and uncertainties existed in modeling trading programs. In practical CET planning issues, various complexities and uncertainties exist among different electricity-generation activities (e.g., coal-fired power, gas-fired power and biomass power) and their socio-economic and environmental implications (e.g., economic penalty, climate policy and emission limitation). These complexities and uncertainties have placed many EPS management problems beyond the conventional optimization methods. In recent decades, many research works have been undertaken for planning CET which corresponds to such uncertainties and complexities (Ermoliev et al., 2015; Mo et al., 2015; Ju et al., 2016). Generally, the above methods can effective for tackling uncertainties expressed as random variables with known probability distributions and fuzzy sets. However, they are incapable of dealing with complex uncertainties presented as interval-random variables and interval-possibilistic parameters (Zhou et al., 2014; Ahmadi et al., 2015; Tan et al., 2015).

Therefore, this study aims at developing a two-stage interval-possibilistic programming (TIPP) model for planning carbon emission trading (CET) of electric power systems (EPS). TIPP will integrate two-stage stochastic programming (TSP), fuzzy-possibilistic programming (FPP), and interval-parameter programming (IPP), which can not only deal with dual uncertainties such as interval-random variables and interval-possibilistic parameters, but also optimize EPS in association with different demand levels. Then, a TIPP-CET model will be formulated for planning EPS in Qingdao (China), where support vector regression (SVR) and Monte Carlo simulation will be integrated into the TIPP-CET framework to predict electricity demand and CO_2 emission. Results will help decision makers to discern optimal power-generation patterns, improve energy supply security and reduce air-pollutant emissions as well as achieve deep insights into the tradeoffs between economic objective and CO_2 emission.

2. Two-stage interval-possibilistic programming

Two-stage stochastic programming (TSP) can effectively tackle uncertainties of the model's right hand sides presented as probability distributions and need to be made periodically over time (Zhu et al., 2015). A general TSP model can be formulated as follows:

$$\text{Min } f = C_{T_1}X + \sum_{h=1}^{s} p_h D_{T_2} Y \tag{1a}$$

Subject to:

$$A_r X \le B_r, \quad r = 1,\ 2,\ \ldots,\ m_1 \tag{1b}$$

$$A_i X + A_i' Y \ge w_h, \quad i = 1,\ 2,\ \ldots,\ m_2; \quad h = 1,\ 2,\ \ldots,\ s \tag{1c}$$

$$x_j \ge 0,\ x_j \in X, \quad j = 1,\ 2,\ \ldots,\ n_1 \tag{1d}$$

$$y_{jh} \ge 0, \quad y_{jh} \in Y, \quad j = 1,\ 2,\ \ldots,\ n_2; \quad h = 1,\ 2,\ \ldots,\ s \tag{1e}$$

where x_j and y_{jh} respectively represent the first- and second-stage decision variables; w_h indicates random variable with probability level p_h (i.e. $h = 1,\ 2,\ \ldots,\ s$, $\sum_{h=1}^{s} p_h = 1$). Summarily, model (1) can handle uncertainties in the right-hand sides expressed as probability distributions, while parameters in the left-hand sides and in the objective function are deterministic. However, in practical EPS planning and management problems, the input data cannot be obtained satisfactory enough as probabilities and may be collected as discrete intervals and possibility distributions. Such complex uncertainties (e.g., interval-random variables and interval-possibilistic parameters) cannot be solved through model (1). Generally, FPP is effective for representing the possible degree of event occurrence for imprecise data described by fuzzy possibility distributions (Zadeh, 1978). IPP approach is effective for tackling the uncertainties expressed as intervals without probability distributions and membership functions (Simic, 2015). Therefore, integrating techniques of FPP and IPP into model (1), a two-stage interval-possibilistic programming (TIPP) model can be formulated as follows:

$$\begin{aligned}\text{Min } \underset{\sim}{f}^{\pm} = {} & \sum_{j=1}^{k_1} \underset{\sim}{c}_j^{\pm} x_j^{\pm} + \sum_{j=k_1+1}^{n_1} \underset{\sim}{c}_j^{\pm} x_j^{\pm} + \sum_{j=1}^{k_2} \sum_{h=1}^{s} p_{jh} \underset{\sim}{d}_j^{\pm} y_{jh}^{\pm} + \sum_{j=k_2+1}^{n_2} \\ & \times \sum_{h=1}^{s} p_{jh} \underset{\sim}{d}_j^{\pm} y_{jh}^{\pm}\end{aligned} \tag{2a}$$

Subject to: