Science of the Total Environment 630 (2018) 469–486

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Analyzing the carbon mitigation potential of tradable green certificates based on a TGC-FFSRO model: A case study in the Beijing-Tianjin-Hebei region, China

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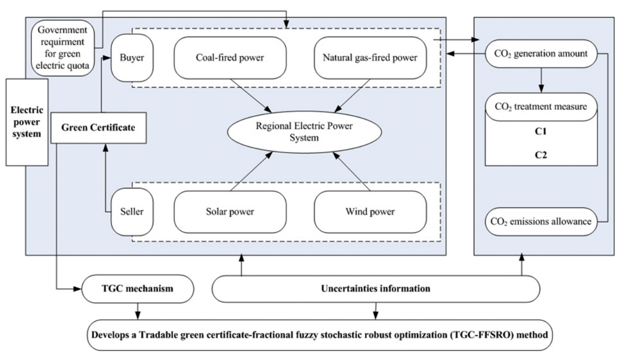
HIGHLIGHTS

- Proposing a tradable green certificate–fractional fuzzy stochastic robust optimization model
- Exploring the carbon mitigation potential of tradable green certificate mechanism
- Analyzing the impacts of TGC mechanisms on electric energy systems
- Dealing with multi-objective tradeoffs between the economy and environment
- Tackling the uncertainties expressed as stochastic and fuzzy sets

GRAPHIC ABSTRACT



ARTICLE INFO

Article history:
Received 17 November 2017
Received in revised form 9 February 2018
Accepted 9 February 2018
Available online xxxx

Editor: Frederic Coulon

Keywords:
Carbon mitigation
Tradable green certificate
Uncertainties
Multi-objective
Electric power system

ABSTRACT

Contradictions of increasing carbon mitigation pressure and electricity demand have been aggravated significantly. A heavy emphasis is placed on analyzing the carbon mitigation potential of electric energy systems via tradable green certificates (TGC). This study proposes a tradable green certificate (TGC)–fractional fuzzy stochastic robust optimization (FFSRO) model through integrating fuzzy possibilistic, two-stage stochastic and stochastic robust programming techniques into a linear fractional programming framework. The framework can address uncertainties expressed as stochastic and fuzzy sets, and effectively deal with issues of multi-objective tradeoffs between the economy and environment. The proposed model is applied to the major economic center of China, the Beijing-Tianjin-Hebei region. The generated results of proposed model indicate that a TGC mechanism is a cost-effective pathway to cope with carbon reduction and support the sustainable development pathway of electric energy systems. In detail, it can: (i) effectively promote renewable power development and reduce fossil fuel use; (ii) lead to higher CO_2 mitigation potential than non-TGC mechanism; and (iii) greatly alleviate financial pressure on the government to provide renewable energy subsidies. The TGC-FFSRO model can provide a scientific basis for making related management decisions of electric energy systems.

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https://doi.org/10.1016/j.scitotenv.2018.02.103

1. Introduction

China is the largest carbon emitter in the world, mainly attributed to its rapid economic development, excessive energy consumption, and "high coal" energy system characteristics (Chen et al., 2018). According to the World Bank, CO_2 emissions from China reached 10.29 billion tons in 2014, accounting for 28.5% of total global CO_2 emissions. The electric energy system is a major contributor to CO_2 emissions in China, accounting for approximately 38% of total CO_2 emissions (Zhu et al., 2013; Man et al., 2017). Excessive CO_2 emissions from the electric energy system is likely to exacerbate problems related to the greenhouse effect, and has thus attracted Chinese government attention and public willingness to reduce carbon emissions (Sun et al., 2017).

Renewable power (e.g., wind and solar) have an enormous potential to satisfy electricity demand while mitigating carbon emissions (Pineda and Bock, 2016; Turk et al., 2018). In recent years, the Chinese government has committed to develop renewable power, especially wind and solar. As part of the United Nations Paris Agreement, the Chinese government promised to increase its renewable energy ratio to 20% by 2020. However, it is difficult for renewable power plants to remain competitive in the current electricity market, because of undeveloped technology, high capital costs, and stochastic weather-dependent production. Subsidies for renewable energy have been adopted as an effective measure to improve the representation of renewable power in the electricity mix, which has led to increasing financial pressure on the Chinese government. Therefore, it is necessary to propose effective pathways for developing renewable power and reducing CO_2 emissions, as well as alleviating financial pressure on the government.

Various studies have been undertaken to tackle the problems discussed above (Tanaka and Chen, 2013; Pineda and Bock, 2016; Atanasoae and Pentiuc, 2017; Kitzing et al., 2017). Among them, a tradable green certificate (TGC) mechanism has been widely adopted as a cost-effective pathway to cope with carbon reduction and renewable power development. It has been successfully applied in many countries (the USA, Japan, France, the Netherlands, Sweden, Denmark, Canada, and Australia) and European member states (e.g., Belgium, Italy, Sweden, the UK, and Poland). Many studies on TGC focus on the interrelationships between the TGC mechanism, electricity market prices, and expansion of renewable power generation. For example, Pineda and Bock (2016) developed a family of generation expansion models to assess the impacts of non-compliance penalties and quota obligations on the expansion of renewable power capacity. Tanaka and Chen (2013) proposed a dominant firm-competitive fringe model to investigate the impacts of the electricity market on renewable certificates and electricity prices. Kitzing et al. (2017) proposed a real options model for investigating the impacts of feed-in tariffs and TGCs on schemes for expansion of renewable power capacity. Atanasoae and Pentiuc (2017) analyzed the impacts of green certificates on electricity production schemes in Romania. According to the Chinese National Development and Reform Commission, TGC mechanisms will be implemented in the electric energy system of China in the near future. Currently, questions remain surrounding the impacts of TGC mechanisms on electricity generation, expansion of capacity, energy resource consumption, system costs, and CO_2 emissions mitigation. However, most previous studies did not adequately analyze the impacts of TGCs on the whole electric energy system.

Moreover, most studies have failed to consider the extensive uncertainties that exist in the electric energy system and raise challenges for electric energy systems planning. For example, electricity demand often expresses stochastic characteristics, which may lead to various electricity generation and capacity expansion activities. Furthermore, CO_2 emissions from various electricity generation activities will be influenced by uncertainties in the electric energy system and uncertain policies surrounding limitations on emissions (Zhu et al., 2013; Chen et al., 2018). Two-stage stochastic programming (TSP) has been extensively adopted as one method for dealing with such uncertainties (Albornoz et al., 2004; Floros and Vlachou, 2005; Chen et al., 2010; Tajeddini et al., 2014; Simic, 2016; Yang et al., 2017). For instance, Tajeddini et al. (2014) employed TSP to analyze the optimal operation of a virtual power plant and its daily operation profits with consideration of risk factors. Simic (2016) proposed a two-stage stochastic full-infinite programming model for managing end-of-life vehicle allocation that can effectively deal with stochastic uncertainties. Yang et al. (2017) employed a TSP model to address uncertainties in equipment capacities, equipment partial load operation, and output bounds as well as in the influence of ambient temperature on gas turbine performance.

However, the TSP method assumes that the decision maker is risk neutral. Thus, it becomes unfeasible when the decision maker is risk averse under conditions of high variability, because it is incapable of considering the variability of recourse values (Ahmed and Sahinidis, 1998; Bai et al., 1997; Chen et al., 2012). Stochastic robust optimization (SRO) can effectively deal with the above issues and generate robust solutions, which bring risk aversion into the TSP optimization model (Mulvey and Vanderbei, 1995; Chen et al., 2012; Ding et al., 2017; Baringo and Amaro, 2017). The RO method penalizes costs that are above the expected values. In addition, RO integrates goal programming formulations with a scenario-based description of problem data, and generates a series of solutions that are progressively less sensitive to realizations of the model data from a scenario set. This makes it especially useful for decision-makers who need to evaluate the trade-off between economic and stability considerations (Mulvey and Vanderbei, 1995; Chen et al., 2018). However, SRO is inefficient in addressing the ambiguity and vagueness of subjective judgments. In practical electric power systems, many economic parameters are not deterministic and often shown as ambiguity, which are suitably expressed as fuzzy sets (Jiménez et al., 2007). Fuzzy possibilistic programming (FPP) can describe this fuzziness in the electric energy system (Zadeh, 1978; Heilpern, 1992; Huang et al., 1993; Jiménez et al., 2007; Fu et al., 2017).

Furthermore, most studies that have aimed to optimize uncertainties in the energy system have mainly focused on economic objectives (i.e., maximizing the energy system benefit or minimizing the system cost), whilst scarcely considering the trade-off between economic and environmental objectives (Li et al., 2017; Yan et al., 2017). Traditional method cannot effectively deal with practical electric energy management problems due to its need to transform multiobjectives into a single measure based on unrealistic or subjective assumptions (Sun et al., 2018). Fractional programming (FP) can compare objectives associated with different aspects directly through their original magnitudes. For FP, optimization of the ratio between economic and environmental qualities can well reflect real-world complexities for electric energy and environment system (Zhu and Huang, 2011; Guo et al., 2014; Yu et al., 2017).

Therefore, this study proposes a tradable green certificate–fractional fuzzy stochastic robust optimization (TGC-FFSRO) model for planning electric energy and reducing CO_2 emissions. The TGC-FFSRO integrates FPP, TSP, and SRO techniques into a FP framework, which can address uncertainties expressed as stochastic and fuzzy sets, and capture risk from stochastic programming, as well as effectively deal with multiple economic and environmental objectives. The proposed model is applied to the Beijing-Tianjin-Hebei (BTH) region, which is one of the most important economic centers in China. The proposed TGC-FFSRO model can: (i) analyze the impacts of a TGC mechanism on the electricity system (i.e., energy allocation, electricity generation, expansion of electric capacity, CO_2 mitigation, and system cost); and (ii) generate optimized schemes for the electric system, including optimized solutions for fossil resource allocation, electricity generation, expansion of electric capacity, CO_2 mitigation, and system cost. The results of this study provide a way to mitigate total CO_2 emissions from the electric energy system via a cost-effective pathway, and can help local managers to adjust current energy and environmental strategies in a sustainable and robust manner.