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An optimization decision support approach for risk analysis of carbon emission trading in electric power systems

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ABSTRACT

Concerns over dramatic increasing electricity demand, exacerbating power shortage and changing climatic condition are emerging associated with municipal electric power systems (EPS). In this study, a risk-explicit mixed-integer full-infinite programming (RMFP) approach is developed for planning carbon emission trading (CET) in EPS. RMFP-CET has advantages in risk reflection and policy analysis, particularly when the input parameters are provided as crisp and functional intervals as well as probabilistic distributions. The developed method is applied to a real case study of CET planning of EPS in Beijing. Various electricity policies are incorporated within the modeling formulation for enhancing the RMFP-CET's capability. The results indicate that reasonable solutions have been generated, which are useful for making decisions of electricity production and supply as well as gaining insight into the tradeoffs among electricity supply risk, system cost, and CO_2 mitigation strategy.

1. Introduction

Since the Industrial Revolution began around 1750, human activities have contributed substantially to climate change by adding CO_2 (carbon dioxide) and other heat-trapping gases into the atmosphere. The risk of climate change due to emissions of greenhouse gases (GHG) from fossil fuels has been considered to be the main environmental threat from the existing energy system (Kosugi, 2009; Swain and Thomas, 2010; Chen et al., 2013; Akhtar et al., 2013; Jordan et al., 2014). Currently, the content of GHG in atmospheric is not declined, on the contrary, increased by about 20% compared with 2000 (United Nations Environment Programme, 2012). About 29 billion tons of CO_2 are released into the atmosphere annually by human activities, including 23 billion tonne from fossil fuel burning and industry (IPCC, 2001). However, fossil fuel still plays a vital role in the global energy system, especially in electricity generation worldwide. In 2012, coal consumption grew by 2.5%. Additionally, coal-fired power plants currently fuel 41% of global electricity (Yang et al., 2013). Such phenomena have resulted in a cost being levied against the environment, which can no longer be treated as a free good, particularly to those countries that ratified the Kyoto Protocol. CO_2 is stipulated to be the biggest one among the other six GHGs, so the calculating unit is per tonne carbon dioxide equivalent in this kind of transaction. Therefore, this transaction was named as “carbon emission trading (CET)”. CET is a form of emissions trading that specifically targets carbon dioxide. This form of permit trading is a common method countries utilize in order to meet their obligations specified by the Kyoto Protocol, which means that the goal of CET is attempt to reduce (mitigate) future climate change. It is necessary to mention that the original idea for emission trading came from Canadian economist John H Dales, as published in his book Pollution Property and Prices (Dales, 1968; Hepburn, 2007). Since then, the idea of trading GHG emissions has become a significant tool to tackle the problem of global climate change. EU Emissions Trading System was the first international policy instrument to introduce regulation of fossil CO_2 emissions.

During the past decades, many scholars employed CET to plan CO_2 mitigation in EPS, while research efforts were mainly based on deterministic mathematical approaches (Haurie and Viguier, 2003; Chappin and Dijkema, 2009; Cong and Wei, 2010; Sadegheih,

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2011; Considine and Larson, 2012; Shen et al., 2012; Chapple et al., 2013; Gerst et al., 2013). For example, Haurie and Viguier (2003) proposed a computable stochastic equilibrium model to represent possible competition between Russia and China on the international market of carbon emission permits. Asano et al. (2007) mentioned that distribution energy resources can substantially reduce carbon emissions, and the presence of generation close the demand can increase the power quality and reliability of electricity delivered to sensitive end-uses. Chappin and Dijkema (2009) presented an agent-based model to elucidate the effect of carbon emission trading on the decisions of power companies in an oligopolistic market. Chicco and Mancarella (2009) reviewed the distributed multi-generation framework, illustrating its characteristics and summarizing the relevant distributed multi-generation structures. Cong and Wei (2010) established an agent-based model to study the potential impact of introduction of carbon emission trading on China's power sector and discuss the impact of different allocation options of allowances; agent-based modeling have ability to overcome some shortcomings of the traditional methods. Sadegheih (2011) proposed an optimization model to search for solutions in power network planning under the carbon emission trading program, which possessed the ability to minimize the total cost with cost-effective and environmentally friendly manner. Alonso et al. (2012) integrated renewable energy sources in smart grids by means of evolutionary optimization algorithms. Considine and Larson (2012) developed an economic model to analyze the underlying economic forces, inducing adjustments in the mix of technologies used in the electric power industry for regulating emissions of GHG emissions, during the first phase of the European Unions Emissions Trading System. Chapple et al. (2013) studied the capital market effects of the proposed emission trading scheme by using of a modified version of the Ohlson valuation model. Bracco et al. (2013) reviewed methods, models, tools, technologies and research challenges in the smart microgrids, and presented the University of Genoa Smart Polygeneration Microgrid. Delfino et al. (2014) proposed a multilevel approach to deal with distributed energy resources, renewables and storage devices connected to microgrids.

However, EPS processes are often associated with various system-failure risks due to the limited resource-availability, the complexity of electricity generation processes, the diversity of management approaches etc. These multiple uncertainties and complexities cannot be regarded as absolute, simplified, or static phenomenon (Zhu et al., 2012; Brauneis et al., 2013; Suo et al., 2013). For example, the desired energy resources allocation patterns may vary with time under high-variability conditions, which may result in a high risk of electricity shortage particularly when energy demand level is high. What's more, carrying out CET is adding new risks that make responsible decision-making even more difficult. Planners are shifting from simply optimizing resource investments assuming a certain future to a different mode of planning, assuming uncertainty. Uncertainty imposes risk, and explicit risk management strategies are being developed (Hyman, 1992; Andrews, 1995; McIntyre and Wheater, 2004). From a system modeling perspective, risks may lie in the value of exogenous inputs and also in the relationships among variables in the system, which caused by the source of the input data, the accuracy of technical and economic data, life cycle of building and facility, the type of energy conversion, the stability of optimization approach, the price range of energy, the length of the analysis phase. Additionally, a representation of risks in a modeling construct may also result from a lack of consensus about assumptions. These risks cannot be controlled by subjective factor of decision maker, which may bring economic loss because of the deviation between pre-estimation and actual results. Investors and managers are typically risk-averse, and thus seek to manage risks. To address the above issues, it is required that the related decisions be made with enhanced security for energy systems. Risk management, is helpful to determine the influence degree caused by the relevant factors of the decision, and determine investment plan or the production schemes for a particular sensitivity of factors' change. It is necessary to identify risk management strategies in the CET of EPS that could address three categories: environmental, value-related, and scope-related risks. Thus, managers can take various measures to reduce the possibilities of risks, or control the possible loss of in a certain range, in order to avoid the losses which are different to bear caused by the occurrence of risk events.

Previously, some research works focused on risk management in EPS (Pinson and Kariniotakis, 2003; Khor et al., 2008; Fan et al., 2010; He et al., 2011; Hurst et al., 2012; Vespucci et al., 2013; Zeng et al., 2013). For example, Douglas et al. (1998) analyzed the risk of short term power system planning, by dealing with uncertainties existing in the process of electrical load forecast. Considering the wind speed forecast imprecision and weather instability, a generic method was presented by Pinson and Kariniotakis (2003) to evaluate short-term wind power forecast risk on-line. Khor et al. (2008) proposed a hybrid of stochastic programming approaches for an optimal midterm refinery planning under uncertainty. In this study operational risk management was considered in petroleum refinery planning. When making investment decisions in a competitive energy market, Fan et al. (2010) developed a risk-averse simulation model to deal with uncertainty about future regulation of CO_2 emissions. He et al. (2011) put forward a model of risk evaluation and applied it to urban power network planning, which would be able to provide theoretical support for urban network planning decisions. Vespucci et al. (2013) analyzed the sensitivity of a two-stage risk neutral stochastic optimization model for power generation capacity expansion planning in a long time horizon, while main results of risk averse strategies were generated under different available budgets. Among these approaches, two-stage stochastic programming (TSP) is effective for handling random variables with known probability distributions. The fundamental idea behind the TSP is the concept of recourse, which is the ability to take corrective actions. In TSP, a decision is first undertaken before values of random variables are known and, then, after the random events have happened and their values are known, a second decision is made in order to minimize “penalties” that may appear due to any infeasibility (Huang and Loucks, 2000; Li et al., 2007, 2011, 2014). However, in TSP, the objective is to minimize the sum of the first-stage and expected second-stage costs, based on an assumption that the decision maker is risk neutral; as a result, TSP may become infeasible when the decision maker is risk averse under high-variability conditions (Li and Huang, 2009). Zou et al. (2010) developed a risk explicit interval linear programming (REIP) method, which could reflect the tradeoffs between risks and system return in a decision-making problem with uncertainty expressed as interval values; a risk function was also defined to enable finding solutions that were feasible and optimal for practical decision making with a maximized system cost and a minimized system risk. However, the REIP was incapable of reflecting dynamic complexities, such as the timing, sizing and siting in planning capacity-expansion schemes. Consequently, a related optimization analysis will always require the use of integer variables to indicate whether a particular facility development or expansion option needs to be undertaken. Mixed-integer programming (MILP) is a efficient tool for this purpose.

Therefore, the objective of this study is to develop a risk-explicit mixed-integer full-infinite programming (RMFP) approach and apply it to planning carbon emission trading (CET) of electric power systems (EPS). RMFP will integrate approaches of two-stage stochastic programming (TSP), risk explicit interval linear programming