Applied Energy 87 (2010) 1033–1047

Contents lists available at ScienceDirect

Applied Energy

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

A two-stage inexact-stochastic programming model for planning carbon dioxide emission trading under uncertainty

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ARTICLE INFO

Article history:
Received 23 June 2009
Received in revised form 7 September 2009
Accepted 12 September 2009
Available online 13 October 2009

Keywords:
Carbon dioxide
Energy
Interval programming
Stochastic
Two-stage
Trading
Uncertainty

ABSTRACT

In this study, a two-stage inexact-stochastic programming (TISP) method is developed for planning carbon dioxide (CO_2) emission trading under uncertainty. The developed TISP incorporates techniques of interval-parameter programming (IPP) and two-stage stochastic programming (TSP) within a general optimization framework. The TISP can not only tackle uncertainties expressed as probabilistic distributions and discrete intervals, but also provide an effective linkage between the pre-regulated greenhouse gas (GHG) management policies and the associated economic implications. The developed method is applied to a case study of energy systems and CO_2 emission trading planning under uncertainty. The results indicate that reasonable solutions have been generated. They can be used for generating decision alternatives and thus help decision makers identify desired GHG abatement policies under various economic and system-reliability constraints.

1. Introduction

Currently, a large amount of electricity relies primarily on non-renewable energy supplies, such as coal, natural gas and petroleum [1]. Greenhouse gas (GHG) is primary gas emitted from these fossil fuels combustion, and increasing concentration of GHG [e.g., carbon dioxide (CO_2)] is likely to accelerate the rate of global warming [2–8]. The present measured concentration of CO_2 in the atmosphere is approximately 30% higher than Pre-Industrial Revolution (1850s) levels [5]. Many scientists concern about the increase of global CO_2 and other GHG emissions, which lead to the increase in surface temperature, the change in the global climate, and the rise in sea level. Some of them question that whether energy supplies can meet GHG mitigation standards with increasing electricity demands. Moreover, a number of researchers are in a puzzle about how to balance increasing electricity demands (due to the population growth and the economic development), less fossil fuel consumption, and mandated requirement for reducing GHG emission [1].

A large number of research works were undertaken for the planning of GHG mitigation in integrated energy and environmental management systems. For example, economic incentive (typically a carbon tax) was proposed to promote less carbon-intensive fuels and to develop alternatives [9]. Renewable energy sources or less GHG intensive fuels were used, such as nuclear power and natural gas [10–12]. Sequestration facilities were built up and used to capture GHG emitted from power plants during electricity generation process [12,13]. Besides, GHG emission trading was envisaged within the Kyoto protocol as one of the so-called flexible mechanisms, it was introduced to help attain reduction of GHG emission in a cost-effective way [14–16]. Previously, deterministic methods were extensively used for managing GHG emission in energy systems [17–23]. However, an integrated energy and environmental management system often contains various uncertainties that may exist in electricity demand and supply, electricity generation processes, related economic parameters, GHG emission inventories, and errors in the measurement instruments. For example, GHG emissions from the electricity generation sector can be influenced by stochastic events such as electricity demand, which may fluctuate from time to time. Meanwhile, the quality of information on generated energy and cost/benefit coefficients are not sufficient, which may vacillate within a certain interval.

As a result, a number of research efforts were conducted for dealing with various uncertainties in the integrated energy and environmental management systems, such as interval mathematical programming (IMP) and stochastic mathematical programming (SMP) [24–29]. IMP allows uncertainties to be directly

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doi:10.1016/j.apenergy.2009.09.016

communicated into the optimization process and resulting solutions, it does not lead to more complicated intermediate models and does not require distribution information for model parameters [30]. Nevertheless, IMP has difficulties when the right-hand sides of a model are highly uncertain, especially with uncertainties expressed as possibilistic and/or probabilistic distributions, which may lead to the loss of valuable information in many real-world decision-making problems [31,32]. In comparison, SMP is effective for decision problems whose coefficients (input data) are uncertain but could be represented as chances or probabilities, which has been extensively applied to energy systems planning [33–36]. Two-stage stochastic programming (TSP) is a typical SMP method, which is an effective alternative for tackling problems where an analysis of policy scenarios is desired and the right-hand-side coefficients are random with known probability density functions (PDFs) [3,37–39]. In TSP, the first-stage decision is to be made before uncertain information is revealed, whereas the second-stage one (recourse) is to adapt to the previous decision based on the further information; the second-stage decision is used to minimize 'penalties' that may appear due to any infeasibility [38,40–45]. However, the major problem of stochastic programming method is that there are increased data requirements for the specification of the probability distribution of the coefficients which may affect the practical applicability [46]. For example, in an integrated energy and environmental system, a planner may know that the daily pollutant and/or GHG emission rate fluctuates within a certain interval, but he may find it is difficult to state a meaningful probability distribution for this variation [31,47]. Therefore, one potential approach for better accounting for the uncertainties and economic penalties is to incorporate the interval-parameter programming (IPP) and TSP techniques within a general optimization framework. This will lead to a two-stage inexact-stochastic linear programming method. For example, Li et al. [29] developed an inexact fuzzy-robust two-stage programming model for managing sulfur dioxide abatement in an energy system under uncertainty, where fuzzy programming was introduced into a TSP framework to deal with uncertainties presented in terms of fuzzy sets and random variables. Huang and Loucks [39] proposed an inexact two-stage stochastic programming (ITSP) model to address the uncertainties. In their study, the concept of inexact optimization was incorporated within a two-stage stochastic programming framework. The model was applied to a case study of water resources management. Moreover, few research works focused on the TSP method for GHG emission trading planning within an integrated energy and environmental management system.

Therefore, the objective of this study aims to develop a two-stage inexact-stochastic programming (TISP) method for CO_2 emission trading planning within an integrated energy and environmental management system. The developed TISP will integrate techniques of IPP and TSP into a general optimization framework. Uncertainties expressed as probabilistic distributions and interval values will be reflected. A case study will then be provided for demonstrating applicability of the developed method. A number of policy scenarios that are associated with different mitigation levels of CO_2 emission permits will be analyzed. The results can help decision makers not only discern optimal energy-allocation patterns, but also gain deep insights into the tradeoffs between CO_2 emission trading and economic objective.

The paper is organized as follows: Section 2 describes the statement of energy and environmental management problem, and formulates the CO_2 emission trading and non-trading models; Section 3 provides the results analysis of the case study; Section 4 discusses the potential limitations and extensions of the proposed TISP method; Section 5 presents conclusions of the work; Appendix A depicts the detailed methodology of the proposed model.

2. Modeling formulation

In an integrated energy and environmental management system, uncertainties may exist in CO_2 generation process and various impact factors, such as CO_2 emission inventory, control measures, and related costs. These uncertainties may affect the endeavors in modeling CO_2 emissions in a power system, which is important for making the integrated energy and environmental management planning. For example, CO_2 emission inventory from the electricity generation sector may vary with the electricity demand, which can be represented as a random variable; the information of cost and benefit coefficients is not sufficient, thus these coefficients can be expressed as interval numbers. An integrated energy and environmental management system can be generally characterized by one or several sources (i.e., the power plant). A large number of CO_2 emissions from these power plants may lead to adverse impacts on climate change. For example, increasing amount of CO_2 in the atmosphere may affect weather condition changes, sea/land ice cover decreases, biodiversity changes, and ecosystem changes.

Since it is generally either technically infeasible or economically impossible to design processes leading to zero emission of CO_2, authorities and decision makers always seek to control the CO_2 emission to level at which the effect is minimized [29]. Therefore, CO_2 mitigation strategy for a power system should include a criterion of allowable levels of CO_2 emissions (i.e., the CO_2 emissions permits) and a scheme for making effective employ of the CO_2 emissions permits. In order to effectively use of emissions permits, it is necessary to carry out the CO_2 emissions trading scheme. Moreover, amounts of CO_2 emissions vary qualitatively and quantitatively from one power plant to another, which can result in huge variations in the cost of achieving targets of emission limits. This difference in cost can also encourage managers of power plants to carry out CO_2 emissions trading scheme [48]. Through trading scheme, each power plant is no longer constrained by its own emission permit but theoretically by the aggregate number of CO_2 emission limit from the power system, which can maximize the system benefit at a certain level of CO_2 emission permit. Since potential energy-demand may vary with the population increase and economic development, which can be expressed as random variable with probability P_{ih} in one case; besides, some uncertain parameters in power system may be expressed as discrete intervals (e.g., the target amount of generated energy, the energy system cost and benefit, the range of CO_2 emission permit, the handling capacity of control measure); furthermore, decisions need to be made periodically over time, and a link to a predefined policy is desired [5,29,49,50]. Therefore, the question under consideration is how to maximize the net benefit of the power system under CO_2 trading scheme while meeting CO_2 emission permit. Thus, the application of TISP model in CO_2 emission trading scheme is considered to be feasible for: (i) meeting the CO_2 emission permit requirement; (ii) maximizing the net benefit of the power system with trading scheme; (iii) recognizing appropriate mitigation plan for CO_2 emissions.

A hypothetical problem is advanced to illustrate the applicability of the TISP approach. The planning horizon of this study is 15 years with three planning periods. This is because, from a long-term planning point of view, CO_2 emission rates may keep increasing due to economic development and energy-demand increase, and the related cost of power system may also vary among different time periods. In this study, three power plants (i.e. one gas-fired power plant, one petroleum-fired power plant, and one coal-fired power plant) are considered as major CO_2 emission sources over the planning horizon. In each power plant, two measures are used to reduce the amount of CO_2 emission: (i) capture and storage (CS), and (ii) chemical absorption (CA). The climate