Energy Conversion and Management 65 (2013) 471–486

Contents lists available at SciVerse ScienceDirect

Energy Conversion and Management

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

Robust planning of energy management systems with environmental and constraint-conservative considerations under multiple uncertainties

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ARTICLE INFO

Article history:
Received 18 June 2012
Received in revised form 23 August 2012
Accepted 3 September 2012
Available online 17 October 2012

Keywords:
Energy management system
Environmental emissions
Robust
Constraint conservativeness
Decision making
Multiple uncertainties

ABSTRACT

In this study, a fuzzy radial interval linear programming (FRILP) model was developed for supporting robust planning of energy management systems with environmental and constraint-conservative considerations, facilitating the reflecting of multiple uncertainties that are existing in energy activities and environmental emissions and could be expressed as fuzzy sets, and regular and radial intervals. Particularly, it could ensure the generation of robust solutions that would be feasible with high probability under input data variations, reflecting tradeoffs between the conservatism levels of solutions and probability levels of constraint violation. Specifically, 24 radial intervals associated with the electricity generation efficiency and electricity demands under different protection levels based on the natural and technologic conditions, as well as decision makers' expectation were determined. Totally, 30 scenarios under the combinations of five protection levels were analyzed. Through solving the developed model, the results showed that decision variables would be rising with the increase of protection levels and higher radii fluctuation levels of radial intervals would cause higher system cost and lower satisfaction degree. The generated solutions could offer detail energy management plans (e.g., energy conversion technology capacity expansions) for decision makers, and thus could guarantee optimal economic and environmental benefits under desirable system reliability.

1. Introduction

'Sustainable development' was defined by Brundtland Commission (1987) as 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs'. Energy is central to improved social and economic well-being, and is indispensable to most industrial and commercial wealth generations. It is the key factor for relieving poverty, improving human welfare and raising living standards [1]. Thus, driving energy systems into a sustainable path has arisen as a policy priority in many countries across the world. Constant endeavor is therefore desired to evaluate various energy-related decisions for meeting increasing energy demands and decreasing the associated emissions. Such a decision-making process is subject to a variety of complexities due to the existence of uncertain factors, dynamic conditions, and component interactions of energy systems. This represents an enormous challenge to decision makers. To deal with such a challenge, development of effective decision-support tools is desired, which could support tradeoff analyses between economic development and environmental protection, and identification of strategies satisfying future energy and environmental requirements [2–4].

In previous studies, a large number of modeling efforts were made for managing energy systems and the associated environmental emissions, such as MARKAL (MARKet ALlocation) model, LEAP (Long-range Energy Alternatives Planning) model, EFOM (Energy Flow Optimization Model), TIMES (Integrated MARKAL–EFOM System), as well as the approaches that were based on multi-objective programming, multi-criteria decision analysis, and strategic planning [5–23]. For example, Liang et al. [5] established a multi-region input–output model for planning energy requirements and CO_2 emissions in China. He also conducted scenario and sensitivity analyses for China's major economic sub-regions in years 2010 and 2020, respectively. Schulz et al. [6] developed a Swiss MARKAL model to manage future energy-related investments in Switzerland. Huang et al. [8] developed a Taiwan LEAP model to predict future energy demands and supplies, and greenhouse gas emissions. Rout et al. [10] adopted the TIMES G5 model to project energy demands and the corresponding emissions in China based on a series of key energy indicators. Pelet et al. [11] employed a

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http://dx.doi.org/10.1016/j.enconman.2012.09.001

multi-objective optimization model to rationalize the design of integrated energy systems through adopting an evolutionary algorithm. Doukas et al. [19] proposed a direct and flexible multi-criteria decision making approach through using linguistic variables to assist policy makers in formulating sustainable energy policies. Terrados et al. [20] carried out regional energy systems planning through adopting strategic planning and SWOT (Strengths, Weaknesses, Opportunities, and Threats) based methods. Becerra-López and Golding [22] applied a multi-objective optimization approach to the capacity expansion of the regional power generation system (RPGS), assuming free competition of technologies, and considering the exergetic and economical costs as the objective functions to be minimized.

Particularly, in most energy-related activities (e.g., energy exploitation, processing and conversion) and the resulting environmental emissions, necessary information of specific model coefficients is probably unavailable. Also, because data are scarce and difficult to obtain, the energy systems being modeled may be subject to changes, resulting in uncertainties and complexities, which cannot be addressed by conventional modeling approaches. Therefore, mathematical programming models for decision support must explicitly tackle the uncertainties associated with model coefficients. The most widely adopted methods handling uncertainties in the planning of energy and environmental systems mainly include interval linear programming (ILP), stochastic linear programming (SLP), and fuzzy linear programming (FLP) [15,24–39,21,40,41]. For example, Cai et al. [24] proposed an inexact community-scale energy model (ICS-EM) for planning renewable energy management (REM) systems under uncertainty based on an integration of the interval linear programming (ILP), chance-constrained programming (CCP) and mixed integer linear programming (MILP) techniques. Rong and Lahdelma [29] employed a multi-period stochastic optimization approach for supporting CO_2 planning emissions trading. Fleten and Kristoffersen [30] developed a short-term production plan for a price-taking hydropower plant operating within a multi-stage mixed-integer linear stochastic programming framework. Zangeneh et al. [32] proposed a static fuzzy multiobjective optimization model to determine the optimal size, location and technology of distributed generation (DG) units in distributed energy systems. Yokoyama and Ito [33] proposed a robust optimal design method based on the relative robustness criterion for the unit sizing of energy supply systems under uncertain energy demands. Cai et al. [35,36] established a large-scale integrated modeling system (IMS) for supporting climate-change impact analysis and adaptation planning under multi-level uncertainties in the Province of Manitoba, Canada. Generally speaking, SLP requires probabilistic distribution information of uncertain parameters which would be hard to be obtained in practical problems. Compared to SLP, ILP is effective in directly communicating uncertain parameters expressed as intervals into optimization processes, but can be adopted only when the range (i.e., lower and upper bounds) of the related coefficient is available, which is insufficient to deal with multi-uncertainties, such as the combination of fuzziness within an individual parameter. This leads to the development of hybrid methods for combining FLP and ILP into a general modeling framework, which is effective to reflect uncertain information in fuzziness and intervals. It could help optimize the system by appraising alternatives under different system satisfaction degrees and provide decision makers decision alternatives under potential system violation risks [42–46]. However, ILP and FLP have the weakness of assuming the range of input data equals to some nominal values. The direct consequence will be that several constraints may be violated and the solutions may no longer be optimal or even feasible when the practical data are inconsistent with the nominal values.

In practical problems, the nominal values of each bound of an interval parameter may fluctuate within a radius causing by the comprehensive influence factors existing in energy systems. This means that it is absolutely essential to apply the radial parameter theory to accept a suboptimal solution for the nominal values to generate feasible and near optimal solutions under the data changes to support the management of energy and environment systems, which is defined as an interval number with each of its bounds being a nominal value fluctuating within a radius. Such a problem can be effectively dealt with through the adoption of robust optimization (RP) (2004). It is a single-stage optimization problem where the uncertainties are defined as inequality constraints subject to a series of user-defined probabilities. Since there are no recourse actions in the programming, computational requirement is significantly reduced. At the meantime, RP is tractable and can generate solutions that are not overly conservative [45,46]. Meanwhile, in RP, the concept of conservation level is introduced to protect against violation of constraints and ensure robust solutions be feasible with high probability. The conservatism level of solutions from the proposed method can make appropriate changes according to probability bounds of constraint violations [50]. Thus, RP could effectively improve upon existing inexact optimization approaches particularly ILP and FLP.

Therefore, in order to comprehensively reflect uncertainties associated with general energy systems and specific environmental emissions, the proposed radial parameter theory and RP will be integrated with ILP and FLP, leading to a fuzzy radial interval linear programming (FRILP) model. The model will then be used for supporting the planning of energy systems with environmental and constraint-conservative considerations under multiple uncertainties. It can excellently enhance advantages and redeem weaknesses of conventional inexact optimization methods. In detail, it can: (a) comprehensively analyze the complex interactions and uncertain information existing in energy-related activities and the resulting environmental emissions, (b) adequately resolve the multiple forms of uncertainties in practical problems, which can be expressed as intervals, fuzzy sets, and radial intervals, (c) guarantee that the system constraints be satisfied with high probability levels as data change within the provided bound radii, and (d) generate robust solutions through balancing the tradeoffs between violation probability and system reliability under acceptable system satisfaction degrees.

2. Environmental emission restrictions and system-constraint conservativeness variations in energy systems

A multitude of factors play a role in comparing energy related options in energy management systems with environmental considerations, such as social-economic costs, pollutant emissions, and domestic energy demands. For developing a sustainable and environmental friendly energy management system, it is of comparative importance to follow an overall system analysis with all levels of internal and external factors. The internal factors mainly indicate the direct energy activities, specifically covering the energy exploration and transportation, energy demand and supply, related conversion technology, and energy policy. Complex interactions exist in the process of converting the primary energy resources to the final production to meet social demands of industry, resident, commerce, transport, and tourist sectors. For example, the energy policy set by authorities will directly restraint energy resource utilization types, and further affect the energy demand and supply, which will finally alter the energy management system structure.

In reality, the tangible or intangible elements in the whole world would all indirectly exert an influence on the energy related activities, forming the external factors. In simple terms, three items of society, economy, and environment are concluded. Concerning