Renewable and Sustainable Energy Reviews 82 (2018) 1056–1067

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

Risk-based electric power system planning for climate change mitigation through multi-stage joint-probabilistic left-hand-side chance-constrained fractional programming: A Canadian case study

Lin Wang[a], Gordon Huang[b,c,*], Xiuquan Wang[d], Hua Zhu[e]

[a] Environmental Systems Engineering Program, Faculty of Engineering and Applied Science, University of Regina, Regina, Saskatchewan, Canada S4S 0A2
[b] Institute for Energy, Environment and Sustainability Research, UR-BNU, University of Regina, Regina, Saskatchewan, Canada S4S 0A2
[c] Institute for Energy, Environment and Sustainability Research, UR-BNU, Beijing Normal University, Beijing 100875, China
[d] School of Geosciences, University of Louisiana at Lafayette, Lafayette, Louisiana 70503, USA
[e] Climate Change Branch, Saskatchewan Ministry of Environment, Regina, Saskatchewan, Canada S4S 0A2

ARTICLE INFO

Keywords:
Electric power system planning
Climate change mitigation
Risk-based management
Multi-stage
Joint-probabilistic programming
Fractional programming

ABSTRACT

Climate change mitigation by reducing greenhouse gas emissions is one of the major challenges for existing electric power systems. This study presents a multi-stage joint-probabilistic left-hand-side chance-constrained fractional programming (MJCFP) approach to help tackle various uncertainties involved in typical electric power systems and thus facilitate risk-based management for climate change mitigation. The MJCFP approach is capable of solving ratio optimization problems associated with left-hand-side random information by integrating multi-stage programming method, joint-probabilistic chance-constrained programming, fractional programming into a general framework. It can balance dual-objectives of two aspects reflecting system optimal ratio and analyze many of possible scenarios due to various end-user demand situations during different periods. The MJCFP approach is implemented and applied to the provincial electric power system of Saskatchewan, Canada to demonstrate its effectiveness in dealing with the tradeoff between economic development and climate change mitigation. Potential solutions under various risk levels are obtained to help identify appropriate strategies to meet different power demands and emission targets to the maximum extent. The results indicate that the MJCFP approach is effective for regional electric power system planning in support of long-term climate change mitigation policies; it can also generate more alternatives through risk-based management, which allows in-depth analysis of the interrelationships among system efficiency, system profit and system-failure risk.

1. Introduction

Earth's climate is warming owing to anthropogenic emissions of greenhouse gases (GHGs), particularly from fossil fuel combustion [1–3]. Almost all energy systems emit GHGs and contribute to climate change [4–6]. Especially, for electric power systems (EPS), satisfying the soaring power demand is a critical strategic goal, but it should be achieved by constructing and upgrading the least economically and environmentally costly power systems [7]. The global electricity supply sector accounts for the release to the atmosphere of over 7700 million tonnes of carbon dioxide annually 2100 Mt C / yr, being 37.5% of total CO_2 emissions [8], and is projected to surpass the 4000 Mt C level by 2020 [9]. A shift towards low-carbon electricity sources has been shown to be an essential element of climate-change mitigation strategies [10]. Consequently, planning of mitigation and adaptation strategies to climate change and power demand requires effective regionalized planning and decision-making behavior [11,12].

A great number of complexities exist in electric power system management [13,14]. The first challenge is to identify a trade-off between conflicting economic and environmental concerns. Achieving solutions to environmental problems that we face today requires long-term potential actions for sustainable development [15]. The second is associated with uncertainties in the system components and parameters. Uncertainties can be derived from related processes and activities (e.g., exploration/exploitation, conversion/processing, and supply/demand), human-induced imprecision or fuzziness, such as lack of available data and biased judgment (or preferences) in assigning priority factors (weighting levels) to multiple management objectives [16,17]. The third challenge is the reflection of dynamic characteristics over the long-term planning horizon. For example, the various

* Corresponding author at: Institute for Energy, Environment and Sustainable Communities, Regina, Saskatchewan, Canada S4S 0A2.
E-mail addresses: lin290@uregina.ca (L. Wang), gordon.huang@uregina.ca, huang@iseis.org (G. Huang), xiuquan.wang@gmail.com (X. Wang), zhu.marie@gmail.com (H. Zhu).

http://dx.doi.org/10.1016/j.rser.2017.09.098
Received 10 May 2016; Received in revised form 9 May 2017; Accepted 25 September 2017

electricity demands have long challenged electric power systems (EPS) planners and managers [18]. It is often influenced by many powerful and unpredictable factors, such as economy, generation technologies, fuel prices, and relevant policy [18]. Therefore, efficient mathematical programming techniques for planning EPS management and climate change mitigation under these complexities are desired.

In past decades, a great number of optimization methods have been developed for dealing with electric power system management problems [19–22] and climate change mitigation [23–25], such as fuzzy programming, stochastic programming and interval mathematical programming [26]. For example, Zhu et al. [23] developed a full-infinite interval-stochastic mixed-integer programming (FIMP) method for planning carbon emission trading. Hemmati et al. [27] proposed a constrained nonlinear mixed integer optimization programming for transmission expansion planning in an electricity market. In these methods, the use of scenarios to model uncertainties in planning models has become increasingly popular [28]. For instance, Dayhim et al. [29], and Kim et al. [30] used a scenario based approach to capture the uncertainty in our study. The multi-stage stochastic programming (MSP) method was found to be effective in reflecting uncertainties expressed as random variables with known probabilities, which permitted revised decisions at each time stage according to the sequential realized uncertain issues [31,32]. Therefore, a number of multi-stage stochastic programming (MSP) methods were developed as extensions of dynamic stochastic optimization methods to deal with system dynamic features [33–35]. Although MSP is suitable for solving long-term planning problems, it is incapable of accounting for the risk of violating joint-probabilistic constraints within a complicated electric power system [36]. Improving upon the conventional right-hand-side chance-constrained programming, joint-probabilistic left-hand-side chance-constrained programming can not only reflect left-hand-side random variables (the relationship between carbon emissions and power generation amounts) but also examine the risk of violating the system constraints [37], especially the risk of high carbon emissions.

However, practical electric power system management and climate change mitigation activities often relate to multiple economic and environmental objectives which may be conflicting with each other, and MSP cannot identify a balanced decision among those conflicting objectives. Multi-objective programming models are helpful to deal with these problems, but most of the previous studies simply translated environmental targets into constraints, where the objective function was purely economic [38,39]; others assumed that environmental impacts could be evaluated as costs and thus converted all units into objective item [21,40,41]. As an effective measure to balance conflicting objectives, fractional programming (FP) may better fit real world problems by taking the optimization of the ratio between the physical and economic quantities into consideration [42]. For example, Zhu et al. [43] suggested that treating multiple economic and environmental objectives as a least-cost linear programming (LP) frame may not reflect the complexities of an environmental sustainability perspective. This indicates a fractional programming, as an alternative method for dealing with multi-objective problems, is practically suitable to achieve desired solutions related to system efficiency.

Therefore, a multi-stage joint-probabilistic left-hand-side chance-constrained fractional programming (MJCFP) approach will be proposed in this study to help tackle various uncertainties involved in typical electric power systems and thus facilitate risk-based management for climate change mitigation. In detail, fractional programming will be first incorporated within an MSP framework to address multiobjective issues. Joint-probabilistic chance-constrained programming will then be introduced to tackle stochastic problems associated with left-hand side random variables and reflect the risk of violating system carbon emission constraints under uncertainty. The MJCFP approach can balance dual-objectives of two aspects reflecting system optimal ratio and analyze many of possible scenarios due to various end-user demand situations during different periods. It thus can help decision-makers identify the optimal electric power system management strategies and gain deeper insights into system efficiency, system profit and system-failure risk under different GHG emission targets. The proposed approach will be further implemented and applied to the provincial electric power system of Saskatchewan, Canada to demonstrate its effectiveness in dealing with the tradeoff between economic development and climate change mitigation.

2. Saskatchewan electric power system

2.1. Overview

As Saskatchewan's economy and population continue to grow, so does the need for electricity which takes power to grow. Saskatchewan electricity sales volumes are expected to increase by 29% over the next ten years [44]. Provincial load growth forecasts indicate the need for an additional 5929 GWh over the next decade [44]. The principal electric utility in Saskatchewan manages a net generating capacity of 3451 MW that includes hydro (21%), thermal coal (41%), thermal gas (33%), and wind (5%) by operating three coal-fired power stations, seven hydroelectric stations, six natural gas stations, and two wind facilities [45]. The system is illustrated in Fig. 1. These energies are consumed by the residential, farm, commercial, oilfield, power and reseller sectors. During the next decade, the system peak demand is expected to increase by approximately 2.2% per year, double the 1.1% per year recorded between 2000 and 2010 [44]. Three conventional coal-fired power plants comprise 1682 MW of this capacity being used to meet base load needs. The generation capacity of natural gas facilities, hydro facilities, wind facilities and cogeneration facilities are 813 MW, 853 MW, 161 MW and 438 MW [46]. From a long-term planning point of view, the planning horizon of this study is 15 years with three planning periods, from 2015 to 2030.

In 2010, Saskatchewan's GHG emissions were 69.8 t/capita (t/c), about 3.5 times the national average [45]. The electricity sector comprises 22% of the province's GHG emissions. Thus, the fact that Saskatchewan's electricity sector accounts for significant emissions must be viewed and considered in the study that Saskatchewan's greenhouse gas emissions are unacceptably high. These power stations pose two challenges for the provincial electric power system: they are very significant GHG emitters and, they are reaching the end of their useful life. Especially, new federal regulations took effect on July 1, 2015, that significantly impacted coal fleet in Saskatchewan. The performance standard for new coal-fired electricity generation units in Canada is supposed to be 420 t/GWh [44]. New and end-of-life units that incorporate technology for carbon capture and storage (CCS) might apply for an exemption from the performance standard until 2025 [47]. The decisions required of SaskPower by concerning investments in replacement generating facilities, simultaneously, meeting burgeoning demand for additional power will set the course for the corporation for coming decades.

2.2. Statement of problems

Electric utilities in Saskatchewan operate in the second largest service area in Canada and has the lowest customer density of any Canadian utility [44]. These electric utilities is committed to supporting economic growth in the province through the delivery of reliable, affordable and sustainable power to Saskatchewan's people, as customers, business owners, and residents, to give them the power to live well [48]. Like any electrical utility in other areas, the system faces many challenges, not the least of which is adapting to a future that includes significant changes in climate and international, as well as local, responses to those changes. Saskatchewan's electric utilities also have adaptation opportunities that could benefit the province, both from economic and climate change mitigation.

In the Saskatchewan electric power system, there are significant