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A pseudo-optimal inexact stochastic interval T2 fuzzy sets approach for energy and environmental systems planning under uncertainty: A case study for Xiamen City of China

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HIGHLIGHTS

- Propose a new energy PIS-IT2FSLP model for Xiamen City under uncertainties.
- Analyze the energy supply, demand, and its flow structure of this city.
- Use real energy statistics to prove the superiority of PIS-IT2FSLP method.
- Obtain optimal solutions that reflect environmental requirements.
- Help local authorities devise an optimal energy strategy for this local area.

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ABSTRACT

In this study, a new Pseudo-optimal Inexact Stochastic Interval Type-2 Fuzzy Sets Linear Programming (PIS-IT2FSLP) energy model is developed to support energy system planning and environment requirements under uncertainties for Xiamen City. The PIS-IT2FSLP model is based on an integration of interval Type 2 (T2) Fuzzy Sets (FS) boundary programming and stochastic linear programming techniques, enables it to have robust abilities to the tackle uncertainties expressed as T2 FS intervals and probabilistic distributions within a general optimization framework. This new model can sophisticatedly facilitate system analysis of energy supply and energy conversion processes, and environmental requirements as well as provide capacity expansion options with multiple periods. The PIS-IT2FSLP model was applied to a real case study of Xiamen energy systems. Based on a robust two-step solution algorithm, reasonable solutions have been obtained, which reflect tradeoffs between economic and environmental requirements, and among seasonal volatility energy demands of the right hand side constraints of Xiamen energy system. Thus, the lower and upper solutions of PIS-IT2FSLP would then help local energy authorities adjust current energy patterns, and discover an optimal energy strategy for the development of Xiamen City.

1. Introduction

Energy is one of the building blocks to improve and/or maintain human daily life. The reasonable allocation of energy sources is one key to achieve high efficiency of energy usage and environmentally friendly society. Since Xiamen City was developed as one of "Special Economic Zones" in 1980 China, it has achieved great economic growth. However, at the same time, the rate of its energy consumption has increased significantly from that time. In order to increase of economic, many energy consumption industries, for example the power industries, have expanded their output capacity. This trend of increasing energy consumption will continue to rise due to the obligation of the national "12th five-year plan" with a proposed economic growth yearly rate of 7% [1]. However, China national energy conservation and low-carbon policies require industrial emissions to be done in an environmentally friendly manner [2]. Thus, the planning of greenhouse-gas (GHG) emission control and energy systems management, (especially

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with coal as main energy sources in China) is necessary and has attracted many scholars' interest over recent years. Energy authorizes need to concern themselves with the balance of energy consumption with emissions' control [3]. However, in energy systems, there are uncountable influencing factors, upon which energy managers should reflect in their allocation strategies [4,5,6,7,8,9,10]. Uncertainties also exist in energy collection, treatment and the conversion processes. For example, the heating value of coal has different values in different production areas. This may cause uncertainties in the consumption of coal to reach a specific gross heating value for an electricity plan. The energy transportation, as a coal property, may have uncertain factors, which are represented in interval data, fuzzy vague and stochastic features. Those uncertain issues may result in a complicated a management procedure, which may be connected with environmental and social economic factors for Decision Makers (DMs) [11,12,13,14,15]. Therefore, development of effective optimization methods to support energy and environmental management under uncertainties and complexities are desired, especially in such "economic zone city" with its limited energy sources and high standards of environmental requirements in the east of China.

1.1. Research background

In past decades, a large number of optimal research works made proposals to deal with such uncertainties and resulted in a compromise between environmental and economic targets [16] required in the planning of energy systems [17,18,19,20,21,22,23,24,25]. In these works, optimization programming played a significant role by providing desired decision alternatives under such complex energy systems [26,27,28,29,30,31,32,12,13,14,10,33,34,24]. For example, a hybrid inexact chance-constrained missed-integer linear programming method was introduced by Liu et al. [19] for nonrenewable energy resources management under uncertainty. This method emphasized an energy allocation pattern with dynamic features. Shrestha and Marpaung [35] examined the implications of a carbon tax for power industries, consuming side programs and pollution emissions in Indonesia. Zhang et al. [36] analyzed the relationship between GHG emission and the power industry to reveal difficulties between regional variations and economic constraints. Lin et al. [37] proposed a longer term energy model to evaluate the economic and environmental performance of the Saskatchewan energy systems [31] proposed a general model for minimizing the cost that finds an optimal combination of energy modules for a country community. Cai et al. [12–14] developed a fuzzy-random interval programming model to identify optimal strategies in the planning of energy management systems under multiple uncertainties. Li et al. [10] developed a multistage interval-stochastic regional-scale energy model to reflect dynamic decisions for power generation schemes. Liu et al. [38] introduced an inexact mix-integer two-stage programming model for management of low carbon energy systems to handle complexities related to carbon mitigation issues which can be effectively reflected. Zhang and et al. [39] compared new-types of bricks make of fly ash and coal gangue and conventional types of bricks to take as examples to analyze the energy saving. Pisello et al. [40] investigate how buildings energy performance is influenced by Inter-Building Effects (IBE) by using building modeling and energy performance assessment models. Ferrante [41] presented alternative ways of investigating, planning and managing sustainable urban environments, by discovering the possibility to use energy retrofitting options as a socio-economic leverage toward nearly Zero Energy Buildings (nZEBs). Aerts et al. [42] developed a probabilistic model which generates realistic occupancy sequences to simulate the more accurate energy demands. Although previous research papers were actual illustrated problems in energy generation, none of them connected energy systems with both the economic requirement and the environmental standards to produce solutions to satisfy each aspects of these components in one general optimization modeling work. Other problems are that those studies barely revealed a multi-factories, multi-time and multi-option with multi-expert experiences. There studies however, deal little with the ambiguity in data estimation, poor variable measurements, or the imprecise information from the subjective assessment.

Of the above mentioned optimization methods, the Interval Linear Programming (ILP) approach is deemed the most effective tool to deal with uncertainties. The desirable feature of this method is that it handles uncertainties as interval numbers without distribution or membership functions. Interval parameters can exist in both the object function and right/left hand of constraints. Its characteristics allow uncertain numbers, for example [10,10.2], to directly communicate into processes of energy management. This ILP model can be solved by Two-Step Method (TSM) developed by Huang et al. [43]. It does not cause complicated intermediate models, and it requires a relative lower level of computations. The typical application of this method is the grey linear programming approach for solid waste management by Huang and Moore [44]. Bass et al. [45] also proposed a grey mathematical program with interval parameters for assessing the sensitivity of a decision to climatically sensitive parameters. However, this conventional interval method only solves a small range interval numbers. This methodology may generate highly uncertain solutions if the interval ranges, (such as [2,20,000]) are very large. Furthermore, ILP only solve those intervals which contain deterministic boundaries. It is based on determined boundary conditions. However, in real world energy systems, this assumption cannot reflect all uncertain issues. Therefore, the ILP method may not be able to fully describe uncertain issues.

In management of energy systems, uncertainty is always accompanied by random and imprecise information or data records. The Fuzzy Linear Programming (FLP) method is an effective method for handling such uncertain problems as fuzzy sets as extensions of the corresponding definitions for ordinary sets. It allows uncertainties to be linked into the optimization process and result in a deductively rational solution of linguistic ambiguity [46,47]. For example, [48] developed an interactive fuzzy Multi-Objective Programming (MOP) model for planning water resources under uncertainties which are represented in terms of fuzzy sets. However, the conventional FLP can only solve problems with determined membership functions, which may be difficult to obtain in a real cases. Therefore, [49] proposed a hybrid method integrating ILP and FLP into an optimal model called as Interval-Fuzzy Linear Programming (IFLP). Following this proposal many studies of interval analysis with fuzzy sets theory were undertaken. The most in-depth study is that of Moore and Lodwick [50]. In this study, the relationship of intervals to fuzzy sets had been provided. IFLP improved on the deficiencies of ILP and enhanced the applicability of FLP. However, it contains shortages of input data which may only be discrete intervals, while deterministic values may still be hard to be estimated under all cases of uncertainties.

Stochastic Mathematical Programming (SMP) is an effective tool to analyze of random variables with probability distribution. It divides decision variables into two subsets. The fundamental concept behind the SMP is its ability to take corrective actions after a random event takes place [51]. It reflects the dynamic variations features of management problems, particularly for large-scale problems. For example, during the typhoon season in Xiamen City, the energy supply has critical importance for people who live in this city. Typhoons in this city bring random factors. Thus, during typhoon season, the use of energy including power, natural gas, renewable energy as well as energy costs show random uncertain. The cost of energy can be expressed as the random interval of