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# Development of an integrated optimization method for analyzing effect of energy conversion efficiency under uncertainty – A case study of Bayingolin Mongol Autonomous Prefecture, China

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ABSTRACT

In this study, a superiority–inferiority full-infinite mixed-integer programming (SFMP) method is developed for analyzing the effect of energy conversion efficiency under uncertainty. SFMP can effectively tackle uncertainties expressed as fuzzy sets, crisp intervals and functional intervals, it also can directly reflect relationships among multiple fuzzy sets through varying superiority and inferiority degrees with a high computational efficiency. Then the developed SFMP is applied to a real case of planning energy system for Bayingolin Mongol Autonomous Prefecture, where multiple scenarios related to different energy-conversion efficiency are concerned. Results for energy processing, energy conversion, capacity expansion, pollutant emission and system cost have been generated. It is proved that SFMP is an effective approach to deal with the uncertainties in energy systems with interactive and uncertain characteristics. A variety of uncertainties existed in energy conversion processes and impact factors could affect the modeling result. Results show that improvement of energy-conversion efficiency can effectively facilitate reducing energy resources consumption, optimizing energy generation pattern, decreasing capacity expansion, as well as mitigating pollutant emissions. Results also reveal that, for the study area, electric power has a highest energy saving potential among heating, oil processing, coal washing and refining. Results can help decision makers to generate desired alternatives that can facilitate policy enactment of conversion efficiency improvement and adjustment of regional energy structure under uncertainty.


## 1. Introduction

It is well known that energy has become an indispensable necessity for the social and economic development. Meanwhile, the soaring energy consumption due to rapid expansion of industry and increasing population, resulted from the emission of pollutants, is threatening the life of human beings. Statistics show that traditional fossil energy resources like natural gas, oil and coal take a large proportion of total energy use in many countries [1]. Nevertheless, the traditional modes of resources exploitation, processing and utilization have shortcoming of low energy efficiency, high energy consumption and high emission, resulting in great waste of resources and serious environmental pollution. Particularly, in China, the thermal power industry occupies a high proportion (72.3%) in the total installed capacity [2], while its conversion efficiency is only 36.5%, lagging behind the countries like Japan and Korea. Moreover, low energy-conversion efficiency could hinder the utilization of renewable energy. For example, for solar photovoltaic industry, the cost can be reduced about 7% when conversion efficiency increases around 1% [3]. Thus, improvement of energy-conversion efficiency is considered as one of the most effective ways to enhance security of energy supply and reduce emissions of pollutants [4].

Over the past decades, many research works were conducted for assessing the effect of energy efficiency on energy systems [5–9]. For example, Ashina and Nakata [10] developed a regional energy-economic model to analyze the impacts of energy efficiency strategies for reducing residential $CO_2$ emissions on energy systems in Japan; the results showed that, if half of the households

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use energy efficient appliances, $CO_2$ emissions from the residential sector in 2020 would decrease. Lopez-Pena et al. [11] used a policy-oriented model of the entire Spanish energy system to assess the effect of energy efficiency promotion and renewable electricity in Spain; results revealed that improved energy efficiency could save more than 5 billion per year for the reduction of $CO_2$ emissions. Drumm et al. [12] established an energy management system to analyze the energy efficiency in the process of industry, which showed that the industry can reduce energy losses by 50% when plant uses more energy-efficient operations. Jiang et al. [13] employed an energy input–output model to investigate the energy saving potential associated with firm ownership-related differences in energy efficiency; their results concluded that China could save up to 20.3% of energy use if industrial could duplicate the energy efficiency. However, few of them took uncertain information of energy systems into consideration, and these uncertainties could make energy systems planning problem become more complicated and beyond the conventional methods.

In the real-world energy systems, a variety of complexities and uncertainties exist in energy conversion processes and various impact factors, such as various energy exploitation techniques, varied energy consumption rate, changed energy processing and conversion efficiency, fluctuant fuel and electricity prices, diverse environmental policies as well as different end-users [14–17]. Among them, the variation of energy-conversion efficiency can affect the energy consumption, energy structure, pollutant emission, capital investment, and facility expansion. Improved energy-conversion efficiency may help cut energy producing cost, avoid unnecessary capital investment, eliminate pollutant emission, and improve energy supply security. Thus, innovative system analysis techniques which can be employed to assist the energy systems planning under uncertainty and analyze tradeoffs among various economic and environmental factors are desired.

Previously, interval-parameter programming (IPP) was received a considerable attention for energy systems planning due to its practicability in allowing uncertain inputs to be communicated into the optimization process and solving complex large-scale problems [18–21]. However, the conventional IPP can only deal with inputs expressed as crisp intervals ([a, b]), whose lower and upper bounds (a and b) are both deterministic and definitely known. This definition is not suitable for all cases where these interval coefficients are affected by external impact factors. Consequently, full-infinite programming (FIP) was proposed to tackle the uncertainties expressed as crisp intervals and functional intervals [22]. Besides, in energy systems planning problems, many parameters may be subject to uncertainties expressed as a combination of intervals and fuzzy sets. Fuzzy mathematical programming (FMP) was capable of handling uncertainties presented as fuzzy sets, and was effective in reflecting ambiguity and vagueness in energy system. In order to solve the FMP problems, various approaches were proposed through utilizing ranking operations and discretizing fuzzy sets via $\alpha$-cuts [23]. However, these methods could generate a large number of additional constraints and variables, resulting in complicated and time-consuming computation processes. Superiority–inferiority fuzzy programming (SIFP) approach could reflect relationships among multiple fuzzy parameters through varying superiority and inferiority degrees (instead of various discrete intervals under different $\alpha$-cut levels), leading to reduced computational requirement and improved practical applicability [24,25].

Therefore, the objective of this study is to develop a superiority–inferiority full-infinite mixed-integer programming (SFMP) method for assessing the effect of energy-conversion efficiency under uncertainty. In SFMP, techniques of fuzzy mathematical programming (FMP) with superiority and inferiority measures will be integrated into an interval full-infinite mixed-integer programming (IFMIP) framework. SFMP can effectively solve parameters uncertainties expressed as a fuzzy set, crisp intervals and functional intervals, it also can directly reflect relationships among fuzzy parameters through varying superiority and inferiority degrees with a high computational efficiency. The developed SFMP will be applied to a real case of planning energy system for Bayingolin Mongol Autonomous Prefecture, where different scenarios related to energy-conversion efficiency will be concerned. The results can be used for analyzing the effect of energy-conversion efficiency on energy systems, and helping decision makers identify the desired energy policy under uncertainty.

## 2. Methodology

An interval mixed-integer linear programming (IMILP) model can be defined as follows [26]:

$$\text{Min } f^{\pm} = C^{\pm}X^{\pm} \tag{1a}$$

subject to:

$$A^{\pm}X^{\pm} \leqslant B^{\pm} \tag{1b}$$

$$X^{\pm} \geqslant 0 \tag{1c}$$

where $X^{\pm} \in \{R^{\pm}\}^{n\times l}$, $C^{\pm} \in \{R^{\pm}\}^{l\times n}$, $A^{\pm} \in \{R^{\pm}\}^{m\times n}$, $B^{\pm} \in \{R^{\pm}\}^{m\times l}$, $R^{\pm}$ denotes a set of interval numbers; $A^{\pm} = (a_{ij}^{\pm})_{m\times n}$, $C^{\pm} = (c_1^{\pm}, c_2^{\pm}, \ldots, c_n^{\pm})$, $B^{\pm} = (b_1^{\pm}, b_2^{\pm} \ldots, b_m^{\pm})^T$ and $X^{\pm} = (x_1^{\pm}, x_2^{\pm}, \ldots, x_n^{\pm})^T$; $X^{\pm}$ are decision variables that can be sorted into two categories: continuous and binary; the '−' and '+' superscripts denote the lower and upper bounds of parameters/variables, respectively.

Despite the effectiveness of the above methods in solving models containing interval-parameters, they still limited for tackling functional intervals [27]. When parameters expressed as functional interval in constraints and objectives, the lower and upper bounds of crisp intervals can vary with its independent variable. Under the circumstance of an infinite number of constraints and objectives, it is necessary to introduce full-infinite programming into IMILP. Therefore, an interval full-infinite mixed-integer programming (IFMIP) can be formulated as follows:

$$\text{Min } f^{\pm} = C^{\pm}(s_0)X^{\pm}, \quad \text{for all } s_0 \in [sl_0, su_0] \tag{2a}$$

subject to:

$$A^{\pm}(s_i)X^{\pm} \leqslant B^{\pm}(s_i), \quad \text{for all } s_i \in [sl_i, su_i] \tag{2b}$$

$$X^{\pm} \geqslant 0 \tag{2c}$$

where $A^{\pm}(s_i)$ $B^{\pm}(s_i)$ and $C^{\pm}(s_0)$ are the function interval parameters; $s_i$ is independent variable in the function of coefficient $A$; $s_0$ is independent variable in the function of coefficient $C$. These parameters should be satisfied under all possible levels within the range of $[sl, su]$. However, in the real-world energy systems, many parameters may be subject to uncertainties expressed as a combination of intervals and fuzzy sets, and IFMIP method sill has limitations for tackling ambiguous or vague information.

Fuzzy programming (FP) is capable of handling uncertainties presented as fuzzy sets, and is effective in reflecting ambiguity and vagueness in resource availabilities that present on the right-hand sides of the model [28,29]. Thus, to deal with uncertain parameters presented as interval values and fuzzy sets, a fuzzy full-infinite mixed-integer programming (FFMP) method is provided as follows:

$$\text{Min } f^{\pm} = C^{\pm}(s_0)X^{\pm}, \quad \text{for all } s_0 \in [sl_0, su_0] \tag{3a}$$

subject to:

$$A^{\pm}(s_i)X^{\pm} \leqslant B^{\pm}(s_i), \quad \text{for all } s_i \in [sl_i, su_i] \tag{3b}$$