A generalized fuzzy chance-constrained energy systems planning model for Guangzhou, China

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Abstract: In this study, a generalized fuzzy chance constrained programming method is developed for the energy system planning in Guangzhou under multiple uncertainties. Through integrating the generalized fuzzy programming and chance-constrained programming into an inexact optimization framework, this method can handle uncertainties expressed as probability distributions, fuzzy sets and fuzzy random variables. Solutions of energy supply, power generation, capacity expansion, air pollutant emissions, forest planning, and system cost under different levels of α-cut are obtained considering the constraint violation risk. The results show that the consumption of coal will decline gradually, while natural gas will become the main source of energy supply in the future; the power structure of the city changes from coal to clean energy (e.g., solar, wind, hydro and other renewable energy), and the city's energy supply security is enhanced by stimulating the utilization of renewable energy and reducing the utilization of imported energy. Moreover, a rational use of ecological land is of great significance. Forests can absorb carbon dioxide and will play a positive role in reducing greenhouse effects. When the preferred α value is predetermined by the decision makers, the energy selections can also be obtained directly from the resulting fuzzy membership function. The solutions obtained in the study will help managers to optimize the existing city energy structure, make decisions according to different preferences between system cost and the violation of the constraint, and thus reflect the corresponding energy supply security level.

Keywords: Chance-constrained programming, Energy model, GHG mitigation, energy security, Generalized fuzzy linear programming

1. Introduction

Energy system planning plays an important role in the sustainable development of society and economy. In decades, the depletion of fossil fuels and its negative effects on environment have become a serious problem with concerns. In China, with the rapid development of modern economy, the total energy consumption is growing significantly, causing the unbalance of energy demand and supply [1]. In China, the average annual growth rate of energy production was 5.97% [2]. In addition, the emissions from energy consumption has caused serious air pollution and environmental problems, resulting in serious consequences on human beings [3]. Over 80% of primary energy in the world comes from fossil fuels, while only 16% of global energy consumption comes from renewable energy [4]. Due to the excessive utilization of fossil fuels, environmental pollution and climate change have deteriorated. Meanwhile, renewable energy has aroused widespread public concern [5]. For example, the Guangdong Province has clearly defined the proportion of renewable energy in total consumption. Renewable energy technologies are increasingly becoming an important component of the global energy structure, especially in areas where policies and measures have been developed to promote their utilization [6]. However, such plans have to go through a multiple complicated processes (e.g., energy generation, conversion, transmission, utilization, and pollutant emission control). These complexities can be multiplied by uncertain parameters (e.g., energy requirements, operating costs, processing/conversion efficiency), leading to multi-level uncertainties. In this complicated energy system, various factors, coefficients and parameters need to be analyzed and modeled. These uncertainties will not only lead to the complexity of the capability beyond the deterministic model, but also affect the relevant optimization results and the corresponding decisions. In Guangzhou, due to its higher energy consumption and lower usage of renewable energy sources, unreasonable ecological land use structure and the complexity of energy systems, it is desired to develop energy system planning which can reflect uncertainties and level of energy supply security and environmental consequences.

Previously, a wide range of optimization methods have been proposed for environmental management to deal with various uncertainties and complexities. Fu [7] has been developed an inexact multi-objective programming model for regional economy-energy-environment system management to obtain absolutely “optimal” solutions. Khiareddine [8] presented a techno-economic optimization model, to perform the optimal sizing of a stand-alone hybrid photovoltaic/wind/hydrogen/battery system. M Alipour [9] proposed a new hybrid Multi-Criteria Decision-Making model based on intuitionistic fuzzy sets suitable for uncertain judgments that integrates Intuitionistic Fuzzy Analytic Hierarchy Process and the Cumulative Belief Degree methods to evaluate energy export policy at the strategic level by addressing inherent uncertainties exist in energy-exporting countries. Lu [10] developed an interval-fuzzy possibilistic programming method based on the interval parameter programming, fuzzy possibilistic programming and fuzzy expected value equation within a general optimization framework and applied it to optimize China energy management system with CO_2 emission constraint. Huang [11] provided an inexact-stochastic water management (ISWM) model and applied to a case study of water quality management within an agricultural system. Nematian [12] proposed an extend two-stage stochastic programming with fuzzy variables developed for water resources management under uncertainty. Li [13] presented a procedure for constructing four bootstrap confidence intervals to assess the uncertainty of GHG emission estimates for three non-normal distributions (namely, Weibull, Gamma and Beta). Huang [14] proposed an inexact two-stage stochastic programming (ITSP) model for water resources management under uncertainty. Li [15] provided an inexact multistage stochastic integer programming (IMSIP) method developed for water resources management under uncertainty. Moreover, various methods were adopted to handle uncertainties in energy systems. Zhu [16] proposed an interval-parameter chanced-constrained full-infinite mixed-integer programming (ICFMP) approach for planning energy systems under functional interval uncertainties. Jin [17] developed an interactive fuzzy chance-constrained resolution (IFCR) method for supporting energy systems planning under uncertainty. Liu [18] developed a single-level optimization program (SLOM) integrating regional energy planning and air pollution control for better balancing the contradiction between the system cost and the pollutant emission problems. Fan [19] explored a GFLP method to identify sulphur dioxide mitigation polices in a regional air quality management system. Li [20] presented an interval-fuzzy regional ecosystem management (IF-REM) model to handle uncertainties expressed as fuzzy sets and discrete intervals. Liu [21] proposed a fuzzy random chance-constrained programming method to handle uncertainties expressed as fuzzy set and randomness. Suo [22] provided a type-2 fuzzy chance-constrained programming (TFCP) method for supporting energy systems planning of Shanghai under uncertainty. Nie [23] developed an interval type-2 fuzzy fractional programming method to cope with the type-2 fuzzy uncertainty of electricity demand in electric power system of Beijing. Fan [24] developed a generalized fuzzy linear programming (GFLP) method for dealing with uncertainties expressed as fuzzy sets. GFLP method allows uncertain information to be passed directly to the optimization process and the result of the solutions. Moreover, GFLP can handle the problems with uncertainties in the objective function and constraints. Unlike the traditional fuzzy set whose membership grades are crisp values, membership grades of GFLP are fuzzy sets within [0,1], it increases fuzziness in a description, which means it has an increased ability to handle uncertain information in a reasonable and correct way; therefore, GFLP is capable of tackling fuzzy uncertainty other than conventional fuzzy sets. However, GFLP has difficulties in tackling uncertainties expressed as probabilistic distributions, which may result in missing information if it fails to deal with such uncertain information. Correspondingly, chance-constrained programming (CCP) is capable of not only reflecting probabilistic distribution in right-hand side of constraints, but also providing trade-off between the risk of constraint violation and system cost [25]. In CCP, when left-hand side of constraints is deterministic and right-hand side parameters is random, it leads to an equivalent convex constraint, and the only information required about the uncertainty is the p fractile for the unconditional distribution of right-hand side [26]. Under different probability of violation of system constraints, reasonable and useful decision making can be generated. The results obtained are a trade-off between decision-makers' understanding of environmental, economic and system reliability standards [27]. Currently, few studies of energy systems planning reflected this complex uncertainty. For energy systems of Guangzhou city with duplicate or multiple uncertainties, individual GFLP or CCP can hardly adequately tackle this problems. Therefore, more effective methods are needed to address such uncertainties.

Therefore, the objective of this paper is to develop a generalized fuzzy chance-constrained programming (GFCCP) method for handling energy management uncertainties of Guangzhou expressed as fuzzy sets. In GFCCP, GFLP and CCP will be integrated together to deal with uncertainties expressed as fuzzy sets and fuzzy random variables. The results will generate different energy management models and help decision makers to determine the required energy management alternatives under various system conditions.

2. Method

Generalized fuzzy linear programming method is widely used for uncertainties expressed as fuzzy sets that exist in the left and right sides of constraints and objective function. Applying this method to the MSW management problem, it proves that it has ability to deal with fuzzy uncertainty [28]. The GFLP method is developed to deal with ambiguous coefficients expressed as fuzzy sets in the objective and constraints. The solutions containing such fuzzy information will thus be generated. General GFLP model can be formulated as follows [29]:

$$Max\, f = \tilde{c} \times X \tag{1a}$$

subject to：

$$A \times X \leq \tilde{b} \tag{1b}$$

$$X \geq 0 \tag{1c}$$

where $\tilde{c} \in \{R\}^{1\times n}$, $X \in \{R\}^{n\times 1}$, $\tilde{b} \in \{R\}^{m\times 1}$, $A \in \{R\}^{m\times n}$, and R denotes fuzzy sets, and $\tilde{c} = \left(\tilde{c}_1, \tilde{c}_2, ..., \tilde{c}_3\right)$, $X = \left(x_1, x_2, ..., x_3\right)^T$, $\tilde{b} = \left(\tilde{b}_1, \tilde{b}_2, ..., \tilde{b}_3\right)^T$, $A = \left(a_{ij}\right)_{m\times n}$, $\forall i \in m, j \in n$.

A fuzzy set (A) in X can be defined as $\left\{x, u_A(x) \middle| x \in X, u_A(x) : X \rightarrow [0,1]\right\}$, where $u_A(x)$ is the membership function or grade of membership. The fuzzy parameters can be expressed as the local distribution of membership functions. However, the generalized fuzzy linear programming method cannot handle uncertain parameters with probabilistic distributions. In the real-world energy planning problems, energy availability is often affected by natural and socio-economic factors, such as economy development and population growth. The associated variables are usually random and can expressed as probability distributions.

Chance-constrained programming is useful for handling random uncertainties and analyzing the risks of violating constraints. A general probabilistic stochastic linear programming can be expressed as follows [18]:

$$Min\, \mathrm{f} = C(t)X \tag{2a}$$

subject to:

$$A(t)X \leq B(t) \tag{2b}$$

$$x_j \geq 0, x_j \in X, j = 1, 2, ..., n \tag{2c}$$

Where X is a vector of decision variables, and $A(t), B(t)$, and $C(t)$ are sets with random elements defined on a probability space T, $t \in T$.

To solve this model, an “equivalent” deterministic version will be defined. This can be achieved by using a CCP method, which includes determining a certain level of probability $p_i \in [0,1]$ for each constraint i and assigning a condition that the constraint satisfies at least a probability of $1 - p_i$. Therefore, the feasible solutions is limited by the following constraints:

$$\Pr[\{t | A_i(t)X \le b_i(t)\}] \ge 1 - p_i, A_i(t) \in A(t), i = 1, 2, ..., m \tag{3}$$

when a_{ij} are deterministic and b_i are random for model (3), given the distribution function of $b_i(t)$ as $F[b_i(t)]$, then $b_i(t)_i^{(p)} = F^{-1}(p_i)$. According to the definition of distribution function, we have:

$$\Pr\left[\left\{t \middle| b_i(t) \le b_i(t)^{(p_i)}\right\}\right] = p_i \tag{4}$$

$$\Pr\left[\left\{t \middle| b_i(t) \ge b_i(t)^{(p_i)}\right\}\right] = 1 - p_i \tag{5}$$

If $A_i X = b_i(t)^{p_i}$, thus $\Pr\left[\left\{t \middle| A_i X \le b_i(t)\right\}\right] = 1 - p_i$; if $A_i X \le b_i(t)^{(p_i)}$, then $\Pr\left[\left\{t \middle| A_i X \le b_i(t)\right\}\right] \ge 1 - p_i$. Hence, when a_{ij} are deterministic and b_i are random, constraint (3) becomes linear:

$$A_i X \le b_i(t)^{p_i} \qquad \forall i \tag{6}$$

Where $b_i(t)_i^{(p)} = F^{-1}(p_i)$, given the cumulative distribution function of b_i, and the probability of violating constraint i. The problem with Eq (3) can only reflect the case when A is deterministic. If both A and B are uncertain, the set of feasible constraints may become more complicated. One potential approach to deal with uncertainties in A, B and C is incorporating the generalized fuzzy linear programming with the CCP framework.

Through incorporating the GFLP within the CCP framework, a generalized fuzzy chance-constrained programming (GFCCP) model can be formulated like follows:

$$M\inf = \sum_{j=1}^{n} \tilde{c}_j \tilde{x}_j \tag{7a}$$

Subject to:

$$\sum_{j=1}^{n} a_{ij} \tilde{x}_j \le b_i^{(p_i)}, i = 1, 2, ..., s \tag{7b}$$

$$\sum_{j=1}^{n} \tilde{a}_{ij} \tilde{x}_j \le \tilde{b}_i, i = s+1, s+2, ..., m \tag{7c}$$

$$\tilde{x}_j \geq 0,\ j = 1, 2, ..., n \qquad (7d)$$

GFCCP is not only capable of dealing with uncertainties expressed as fuzzy sets that exist in the constraints' left and right sides and objective function but also capable of dealing with random uncertainties and analyzing the risks of violating constraints. Before solving model (7), fuzzy parameters in model (7) will be defuzzified through the α-cut method. Then, for any $\alpha \in [0,1]$, the associated α-cuts for $\tilde{c}_j$, x_j, a_{ij}, and $\tilde{b}_i$ are fuzzy interval numbers expressed as: $(c_j)^{\pm}_{\alpha_i} = [(c_j)^{-}_{\alpha_i}, (c_j)^{+}_{\alpha_i}]$, $(x_j)^{\pm}_{\alpha_i} = [(x_j)^{-}_{\alpha_i}, (x_j)^{+}_{\alpha_i}]$, $(a_{ij})^{\pm}_{\alpha_i} = [(a_{ij})^{-}_{\alpha_i}, (a_{ij})^{+}_{\alpha_i}]$ and $(b_i)^{\pm}_{\alpha_i} = [(b_i)^{-}_{\alpha_i}, (b_i)^{+}_{\alpha_i}]$. An interval number $(a^{\pm})$ is defined as: $a^{\pm} = [a^{-}, a^{+}] = \left\{ t \in a \middle| a^{-} \leq t \leq a^{+} \right\}$.

α-cut levels are then be rearranged into an increasing sequence: $\alpha_{(1)}, \alpha_{(2)}, ..., \alpha_{(q)}$, where $\alpha_{(1)} \leq \alpha_{(2)} \leq \cdots \leq \alpha_{(q)}$. Then an interval linear programming (ILP) model can be formulated as follows:

$$Max(f)^{\pm}_{\alpha_{(1)}} = \sum_{j=1}^{n} (c_j)^{\pm}_{\alpha_{(1)}} \times (x_j)^{\pm}_{\alpha_{(1)}} \qquad (8a)$$

subject to:

$$\sum_{j=1}^{n} (a_{ij})^{\pm}_{\alpha_{(1)}} \times (x_j)^{\pm}_{\alpha_{(1)}} \leq (b_i)^{\pm}_{\alpha_{(1)}},\ i = 1, 2, ..., m \qquad (8b)$$

$$(x_j)^{\pm}_{\alpha_{(1)}} \geq 0,\ j = 1, 2, ..., m \qquad (8c)$$

Since model (8) is an inexact linear programming model with all parameters expressed as intervals, it can be solved through the interactive algorithm [29]. In detail, the upper-bound sub-model will correspond to $(f)^{+}_{\alpha_{(1)}}$, which can be formulated as:

$$Max(f)^{+}_{\alpha_1} = \sum_{j=1}^{k_1} (c_j)^{+}_{\alpha_{(1)}} (x_j)^{+}_{\alpha_{(1)}} + \sum_{j=k+1}^{n} (c_j)^{+}_{\alpha_{(1)}} (x_j)^{-}_{\alpha_{(1)}} \qquad (9a)$$

Subject to:

$$\sum_{j=1}^{k} Sign((a_{ij})^{\pm}_{\alpha(1)}) \left|(a_{ij})_{\alpha(1)}\right|^{-} (x_j)^{+}_{\alpha(1)} + \sum_{j=k+1}^{n} Sign((a_{ij})^{\pm}_{\alpha(1)}) \left|(a_{ij})_{\alpha(1)}\right|^{+} (x_j)^{-}_{\alpha(1)} \leq (b_i)^{+}_{\alpha(1)}, \forall i$$

(9b)

$$(x_j)^{\pm}_{\alpha(1)} \geq 0, \forall j \quad (9c)$$

Then the lower bound sub-model corresponding to $(f)^{-}_{\alpha(1)}$ can be expressed as follows:

$$Max(f)^{-}_{\alpha_1} = \sum_{j=1}^{k_1} (c_j)^{-}_{\alpha(1)} (x_j)^{-}_{\alpha(1)} + \sum_{j=k+1}^{n} (c_j)^{-}_{\alpha(1)} (x_j)^{+}_{\alpha(1)} \quad (10a)$$

subject to:

$$\sum_{j=1}^{k} Sign((a_{ij})^{\pm}_{\alpha(1)}) \left|(a_{ij})_{\alpha(1)}\right|^{+} (x_j)^{-}_{\alpha(1)} + \sum_{j=k+1}^{n} Sign((a_{ij})^{\pm}_{\alpha(1)}) \left|(a_{ij})_{\alpha(1)}\right|^{-} (x_j)^{+}_{\alpha(1)} \leq (b_i)^{-}_{\alpha(1)}, \forall i$$

(10b)

$$(x_j)^{-}_{\alpha(1)} \leq (x_{jopt})^{+}_{\alpha(1)}, \; j = 1, 2, ..., k_1 \quad (10c)$$

$$(x_j)^{+}_{\alpha(1)} \geq (x_{jopt})^{-}_{\alpha(1)}, \; j = k+1, k+2, ..., n \quad (10d)$$

$$(x_j)^{\pm}_{\alpha(1)} \geq 0, \forall j \quad (10e)$$

We can obtain the solutions of $(x_{jopt})^{-}_{\alpha(1)}$ $(j = 1, 2, ..., k_1)$ and $(x_{jopt})^{+}_{\alpha(1)}$ $(j = k+1, k+2, ..., n)$ through sub-model (8). Therefore, the final solutions for model (7) can be obtained as follows:

$$(x_{jopt})^{\pm}_{\alpha(1)} = \left[(x_{jopt})^{-}_{\alpha(1)}, (x_{jopt})^{+}_{\alpha(1)} \right] \quad (11a)$$

$$(f_{opt})^{\pm}_{\alpha(1)} = \left[(f_{opt})^{-}_{\alpha(1)}, (f_{opt})^{+}_{\alpha(1)} \right] \quad (11b)$$

Afterwards, $\alpha_{(2)}$ to $\alpha_{(q)}$ are selected in sequence and formulated (q-1) ILP sub-models. And the corresponding ILP sub-model can be solved in sequence from 2 to q, through converting it into two sub-models presenting in model (7).

3. Develop of GFCCP-Guangzhou model

Guangzhou, is the political, economic and technological, educational and cultural center of the Guangdong Province in China. It occupies an administrative area of around 7,434.4 km^2 with 11 districts. It is one of the largest cities in China with over 8.54 million population in 2015 [31]. In recent decades, Guangzhou has experienced soaring economic development and continuous population growth, resulting in a highly rapid increment in energy demand. According to Statistics Bureau of Guangzhou, the GDP increased from 107.48 million RMB in 2010 to 167.68 million RMB in 2014 with the average annual growth rate of 13.86%. The economic development of the city is closely related to the energy supply and electric power [32]. However, the domestic energy supply is far from meeting the growing demands of the urban economy. So it is necessary to adjust the current energy structure and the form of power generation. Nowadays, renewable energy resources have been considered as new electricity sources to address the crisis of energy shortages, climate change and air pollution. However, Guangzhou has great potentials for developing renewable energy. It has abundant water, wind and solar energy resources. In the outline of environmental protection plan of Guangdong Province, in order to optimize the energy structure, the use of clean energy should be increased, i.e. natural gas power generation, wind power generation and solar power generation should be further developed. However, there are still a series of problems in the development and utilization of renewable energy resources. Currently, there is a small amount of renewable energy resources used in Guangzhou compared to conventional fossil fuel source. Because fossil fuels (e.g., coal, oil and gasoline) consumption produces a large number of pollutants (e.g., SO_2, NO_X and PM), excessive fossil fuel has brought serious damages to the environment of Guangzhou. According to the “Guangzhou city air pollutant emission inventory report", the amount of SO_2 emission reached 78,000 tonnes and the amount of the NO_X emission reached 231,000 tonnes in 2014. Among them, the fixed combustion of fuel sulfur dioxide (SO_2) accounted for 72%. Although many measures have been taken by the government to improve the environmental quality, the increasing energy demand and consumption would outweigh the great efforts made by government to mitigate the emissions.

Guangzhou's energy system and ecological environment are faced with serious problems including (i) the shortage of resources hardly meets the supply of the energy demands; (ii) although air quality is improving gradually, the air pollution is still serious because of the excessive energy consumption seriously affecting the sustainability of urban energy systems and economic development; (iii) unreasonable ecological land use structure hardly meets the needs of urban development. Since forests can absorb large amount of carbon dioxide and reduce the urban greenhouse effect, ecological land need to be adjusted greatly. With the increasingly growing awareness of environmental protection. The total amount of energy consumed by the local government is controlled by 66 to 70 million tons of standard coal, and the coal is controlled below 14 million tons in 2020. Correspondingly, the use of renewable energy will increase enormously as most of renewable energy sources are clean, and they generate little pollutants. In the recent years, renewable energy were considered as the clean resources to address the crisis of energy shortage, reduce the dependence on external energy supply, and mitigate the air pollutant emissions. Using renewable energy to generate electric is a better choice for decision makers to achieve reduction targets of pollutants emissions. Moreover, encourage the improvement of ecological forest planting also has an indispensable role. In urban energy system planning, there are a number of complex processes (e.g., electricity generation, machining and conversion processes, and pollutant emissions) that should be taken into account by decision makers. In addition, many system parameters like technical factors (e.g., resource availability and conversion efficiency), economic (e.g., capital cost and fuel price) and politic (e.g., power market regulation, emission reduction target) factors may bring uncertainties. Such uncertainties are not only complicated by natural changes of energy resources of Guangzhou, but also further compounded by the economic and environmental impact for their utilization. These uncertainties and complexities should be comprehensively considered by decision makers, and effectively dealing with these problems is greatly significant to decision makers.

The city’s energy system consists of four subsystems, including energy supply, processing and conversion, transmission and demand (as shown in Fig. 1). Multiple conventional and renewable energy resources (i.e. oil products, coke, coal, natural gas, wind and solar) are supplied to meet the city’s energy demand. Two energy processing technologies (i.e. oil refining and coking) and five energy-conversion technologies (i.e. coal-fired power, gas-fired power, wind power, hydroelectric power and photovoltaic power) are considered. The local production of secondary energy include gasoline, diesel oil, fuel oil, liquefied petroleum gas (LPG), coke and electricity. Some of these secondary energy might be imported from other regions due to insufficient local production and supply.

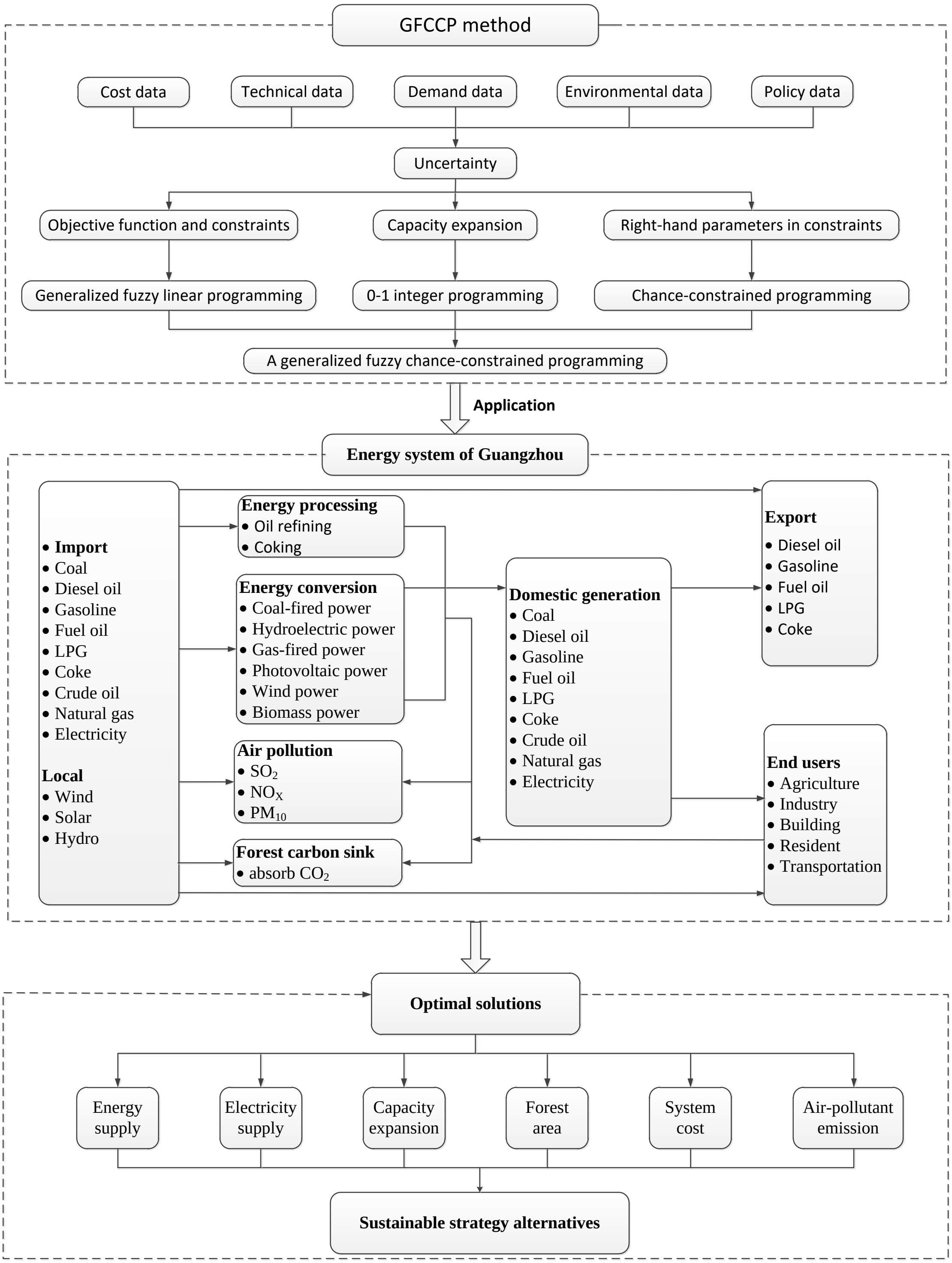


Fig.1. Framework of the GFCCP modeling system

3.1. Model formulation

Based on the aforementioned challenges and problems, GFCCP is applied to the Guangzhou’s energy system planning. Generalized fuzzy linear programming method is widely used for uncertainties expressed as fuzzy sets that exist in the left and right sides of constraints and objective function. all parameters, including various energy import and export costs, processing and conversion costs, expansion costs, and emissions per unit of pollutants, have adopted the generalized linear fuzzy planning method in Section 2, Five α-cut levels are defined for each parameter, including α=0,0.3,0.5,0.8,1. Each α-cut value corresponds to different upper and lower bounds. Also, the right-hand parameter energy availability of the constraint used the Chance-constrained programming mentioned in the Second 2. Chance-constrained programming is useful for handling random uncertainties and analyzing the risks of violating constraints. Under different probability of violation of system constraints, reasonable and useful decision making can be generated. The results obtained are a trade-off between decision-makers' understanding of environmental, economic and system reliability standards.

The objective of the energy planning for Guangzhou is to minimize the total system costs. The objective function considers various costs, including energy import and export cost, processing cost, conversion cost, expansion cost, and pollutant discharge cost. The constraints consider the energy supply and demand balance, energy availability, power supply and demand balance, pollutant emission, carbon dioxide emissions, expansion, forest area, and non-negative constraints. These uncertainties and complexities could be comprehensively considered and be effectively handled through GFCCP, which could provide significant sights for decision makers.The study problem can be formulated as follows:

$$\min f = \sum_{i=1}^{8}\sum_{t=1}^{3}\tilde{J}CB_{it}\tilde{N}CL_{it} + \sum_{i=1}^{8}\sum_{t=1}^{3}\tilde{W}CB_{it}\tilde{W}CL_{it} - \sum_{j=1}^{8}\sum_{t=1}^{3}(\tilde{C}XE_{jt}\tilde{C}XL_{jt} + \tilde{B}XE_{jt}\tilde{B}XL_{jt})$$

$$+\sum_{m=1}^{2}\sum_{t=1}^{3}(\tilde{J}GC_{mt}\tilde{J}N_{mt} + \tilde{J}KC_{mt}\tilde{J}L_{mt}) + \sum_{n=1}^{6}\sum_{t=1}^{3}(\tilde{Z}GC_{nt}\tilde{Z}N_{nt} + \tilde{Z}KC_{nt}\tilde{Z}CL_{nt})$$

$$+\sum_{m=1}^{2}\sum_{t=1}^{3}\left[(\tilde{J}CKC_{mt} + \tilde{J}CGC_{mt})\cdot\tilde{J}KN_{mt}\cdot JSFK_{mt}\right]$$

$$+\sum_{n=1}^{6}\sum_{t=1}^{3}\left[(\tilde{Z}CKC_{nt} + \tilde{Z}CGC_{nt})\cdot\tilde{Z}KN_{nt}\cdot ZSFK_{nt}\right]$$

$$+\sum_{m=1}^{2}\sum_{l=1}^{3}\sum_{t=1}^{3}\tilde{J}WPL_{mlt}\tilde{J}L_{mt}(1-\tilde{J}WHX_{mlt})\tilde{J}WPC_{mlt}$$

$$+\sum_{n=1}^{6}\sum_{l=1}^{3}\sum_{t=1}^{3}\tilde{Z}WPL_{nlt}\tilde{Z}CL_{nt}(1-\tilde{Z}WHX_{nlt})\tilde{Z}WPC_{nlt}$$

$$+\sum_{m=1}^{2}\sum_{t=1}^{3}\tilde{J}JC_{mt}\tilde{J}L_{mt}+\sum_{n=2}^{6}\sum_{t=1}^{3}\tilde{Z}JC_{nt}\tilde{Z}CL_{nt}$$

$$+\sum_{t=1}^{3}(\tilde{Y}GC_{t}-\tilde{D}JY_{t})\cdot\tilde{S}A_{t}+\sum_{t=1}^{3}\tilde{D}JJ_{t}\cdot\tilde{D}DL_{t}$$

(1) Cost of purchasing energy sources

$$\sum_{i=1}^{8}\sum_{t=1}^{3}\tilde{J}CB_{it}\tilde{N}CL_{it}+\sum_{i=1}^{8}\sum_{t=1}^{3}\tilde{W}CB_{it}\tilde{W}CL_{it} \tag{12a}$$

(2) Cost of selling energy sources

$$\sum_{j=1}^{8}\sum_{t=1}^{3}\tilde{C}XE_{jt}\tilde{C}XL_{jt}+\sum_{j=1}^{8}\sum_{t=1}^{3}\tilde{B}XE_{jt}\tilde{B}XL_{jt} \tag{12b}$$

(3) Cost of energy processing and conversion

$$\sum_{m=1}^{2}\sum_{t=1}^{3}(\tilde{J}GC_{mt}\tilde{J}N_{mt}+\tilde{J}KC_{mt}\tilde{J}L_{mt})+\sum_{n=1}^{6}\sum_{t=1}^{3}(\tilde{Z}GC_{nt}\tilde{Z}N_{nt}+\tilde{Z}KC_{nt}\tilde{Z}CL_{nt}) \tag{12c}$$

(4) Cost of capacity expansion

$$\sum_{m=1}^{2}\sum_{t=1}^{3}\left[(\tilde{J}CKC_{mt}+\tilde{J}CGC_{mt})\cdot\tilde{J}KN_{mt}\cdot JSFK_{mt}\right]+\sum_{n=1}^{6}\sum_{t=1}^{3}\left[(\tilde{Z}CKC_{nt}+\tilde{Z}CGC_{nt})\cdot\tilde{Z}KN_{nt}\cdot ZSFK_{nt}\right] \tag{12d}$$

(5) Cost of pollutant reduction

$$\sum_{m=1}^{2}\sum_{l=1}^{3}\sum_{t=1}^{3}\tilde{J}WPL_{mlt}\tilde{J}L_{mt}(1-\tilde{J}WHX_{mlt})\tilde{J}WPC_{mlt} \tag{12e}$$

(6) Cost of CO_2 abatement

$$\sum_{m=1}^{2}\sum_{t=1}^{3}\tilde{J}JC_{mt}\tilde{J}L_{mt}+\sum_{n=2}^{6}\sum_{t=1}^{3}\tilde{Z}JC_{nt}\tilde{Z}CL_{nt} \tag{12f}$$

(7) Cost of import electricity

$$\sum_{t=1}^{3}\tilde{D}JJ_{t}\cdot\tilde{D}DL_{t} \tag{12g}$$

(8) Ecological economic compensation

$$\sum_{t=1}^{3}(\tilde{Y}GC_{t}-\tilde{D}JY_{t})\cdot\tilde{S}A_{t} \tag{12h}$$

subject to:

(1) Energy supply and demand balance constraints

$$\tilde{N}CL_{it}+\tilde{W}CL_{it}\le\tilde{K}NL_{it}\quad(i=j=1,5,7,8)\qquad\forall t \tag{13a}$$

$$\tilde{N}CL_{it}+\tilde{W}CL_{it}-\tilde{C}XL_{jt}-\tilde{B}XL_{jt}\le\tilde{K}NL_{it}\quad(i=j=2,3)\quad\forall t \tag{13b}$$

$$\tilde{W}CL_{it}-\tilde{C}XL_{it}-\tilde{B}XL_{it}\le\tilde{K}NL_{it}\quad(i=j=4)\qquad\forall t \tag{13c}$$

$$\tilde{N}CL_{it}-\tilde{C}XL_{it}-\tilde{B}XL_{it}\le\tilde{K}NL_{it}\quad(i=j=6)\quad\forall t \tag{13d}$$

(2) Energy availability constraints

$$\tilde{N}CL_{it}+\tilde{W}CL_{it}\ge\tilde{Z}X_{it}\quad(i=j=1,5,8)\quad\forall t \tag{13e}$$

$$\tilde{N}CL_{it}+\tilde{W}CL_{it}+a_{mt}\cdot\tilde{J}L_{mt}\ge\tilde{Z}X_{it}\quad(m=1,i=j=7)\quad\forall t \tag{13f}$$

$$\tilde{N}CL_{it}+\tilde{W}CL_{it}+a_{mt}\cdot\tilde{J}L_{mt}\cdot\tilde{F}P_{it}\ge\tilde{Z}X_{it}\quad(m=2,i=j=2,3,4,6)\quad\forall t \tag{13g}$$

$$\tilde{J}CL_{it}=a_{mt}\cdot\tilde{J}L_{mt}\cdot\tilde{F}P_{it}\quad(i=2,3,4,6)\qquad\forall t \tag{13h}$$

$$\tilde{N}CL_{it}+\tilde{W}CL_{it}\ge\tilde{Z}CL_{nt}\cdot ZDFL_{nt}\quad(n=1,i=1)\quad\forall t \tag{13i}$$

$$\tilde{N}CL_{it} + \tilde{W}CL_{it} \geq \tilde{Z}CL_{nt} \cdot ZDFL_{nt} \qquad (n=2, i=8) \quad \forall t \tag{13j}$$

$$\tilde{Z}CL_{nt} / \tilde{F}DXL_{nt} \leq \tilde{K}ZSL_{nt} \qquad (n=3,4,5) \quad \forall t \tag{13k}$$

(4) Electricity balance constraints

$$\tilde{D}DL_t + \sum_{n=1}^{6} \tilde{Z}CL_{nt} \geq \tilde{D}ZL_t \cdot (1 + \tilde{S}SL_t) \qquad \forall t, n \tag{13l}$$

$$\tilde{D}DL_t < \tilde{D}ZL_t \cdot (1 + \tilde{S}SL_t) \cdot \tilde{b}_t \qquad \forall t \tag{13m}$$

$$\tilde{Z}CL_{nt} \geq \tilde{P}EU_{nt} \qquad (n=1,2,3,4,5,6) \quad \forall t \tag{13n}$$

(5) Air-pollutant emission constraints

$$\sum_{m=1}^{2} \tilde{J}WPL_{lmt} \tilde{J}L_{mt} (1 - \tilde{J}WHX_{lmt}) + \sum_{n=1}^{2} \tilde{Z}WPL_{\ln t} \tilde{Z}CL_{nt} (1 - \tilde{Z}WHX_{\ln t}) \leq \tilde{P}EA_{lt} \qquad \forall t \tag{13o}$$

(6) CO2 emission constraints

$$\sum_{m=1}^{2} \tilde{D}JCL_{mt} \tilde{J}L_{mt} + \sum_{n=1}^{2} \tilde{D}ZCL_{nt} \tilde{Z}CL_{nt} - \tilde{D}ST_t \cdot \tilde{S}A_t \leq \tilde{C}E_t \qquad \forall t \tag{13p}$$

(7) Imported electricity constraints

$$\tilde{D}DL_t \geq \tilde{M}DDL_t \qquad \forall t \tag{13q}$$

(8) Capacity of electricity conversion constraints

$$\tilde{J}N_{mt} + \tilde{J}KN_{mt} \tilde{J}SFK_{mt} > \tilde{J}L_{mt} \qquad \forall t \tag{13r}$$

$$\tilde{Z}N_{nt} + \tilde{Z}KN_{nt} ZSFK_{nt} > \tilde{Z}CL_{nt} / (24 \times 365) \qquad \forall t \tag{13s}$$

(9) Binary variable constraints

$$JSFK_{mkt} \begin{cases} =1, \text{ if capacity expansion is undertaken} \\ =0, \text{ otherwise} \end{cases} \qquad \forall k, m \tag{13t}$$

$$ZSFK_{nkt} \begin{cases} =1, \text{ if capacity expansion is undertaken} \\ =0, \text{ otherwise} \end{cases} \quad \forall k, n \tag{13u}$$

(10) Non-negative constraints

$$NCL_{it}, CXL_{it}, JL_{mt}, JCL_{it}, ZCL_{nt}, JKN_{mt}, ZKN_{nt}, WCL_{it}, BXL_{it}, DDL_{t}, SA_{t} \geq 0 \quad \forall i, j, m, n, k \tag{13v}$$

The specific glossary of variables and parameters is given in the Appendix. The 9-year planning horizon (2017-2025) is divided into three periods with three years of each. Because of the extreme resource scarcity, the city's energy supply relies on import from other regions. The city's energy supply relies on the energy processing and conversion, which are the main pollutant-emission sources. And the pollutant emissions from the two progresses are reflected in the constraints. Meanwhile, forests with the feature of carbon dioxide absorption can slow down urban greenhouse effects, which is also considered within the constraints. According to thirteenth five year plan of energy development in Guangzhou[32], compared with traditional fossil-fuel-fired power plant, biomass power generation in Guangzhou is at a low level, because biomass is not readily available locally, as well as a relative high capital investment. Since the emission from biomass combustion is not high within total emissions, it is assumed that its emissions has little impact on the system and thus ignored.

3.2. Input data of case study

Tables 1-3 provide costs of energy purchase, selling, processing, conversion and capacity expansion, which are highly uncertain. In this study, three *p* levels (i.e. 0.01, 0.05 and 0.10) on the energy demand are considered, implying that energy demand should be satisfied at the probabilities of 0.99, 0.95 and 0.90. Different *p* levels on energy demand are helpful for investigating the risks of violating the demand constraint, generating desired solutions of energy.

Table. 1. Cost of energy purchase and selling ($\$10^3$TJ)

	Energy purchase cost			Energy selling cost		
	t=1	t=2	t=3	t=1	t=2	t=3
Coal	[19.8,21.8]	[20.2,22.4]	[21.1,23.31]	[18.4,20.4]	[18.6,21.6]	[20.3,22.5]
Diesel oil	[178.8,197.6]	[181.3,200.3]	[182.6,201.8]	[165.1,182.3]	[170.4,188.4]	[174.4,192.8]
Fuel oil	[128.6,142.2]	[130.3,144.1]	[131.4,145.2]	[126.1,139.3]	[127.9,141.4]	[130.1,143.7]
Gasoline	[157.1,173.7]	[160.7,177.6]	[162.7,179.9]	[152.2,168.2]	[157.1,173.6]	[160.1,176.9]
Crude oil	[127.7,141.2]	[129.7,143.3]	[131.7,145.6]	[129.9,143.5]	[132.4,146.4]	[134.2,148.4]
LPG	[121.0,133.8]	[123.1,136.1]	[125.9,139.1]	[124.4,137.5]	[125.6,138.8]	[128.2,141.6]
Coke	[47.8,52.8]	[50.1,55.3]	[52.9,58.5]	[55.3,61.1]	[57.4,63.4]	[60.4,66.8]
Natural	[51.8,57.2]	[55.9,61.7]	[61.5,67.9]	[53.0,58.5]	[55.5,61.3]	[57.9,64.1]

Table.2. Cost of energy processing and conversion

	Fixed cost			Variable cost		
	t=1	t=2	t=3	t=1	t=2	t=3
Fixed (10^3yuan/TJ) and variable (10^3yuan/TJ) costs for processing technologies						
Oil refining	[29.5,32.6]	[28.1,31.1]	[26.8,29.6]	[24.9,27.5]	[24.9,27.5]	[24.2,26.8]
Coking	[24.8,27.5]	[23.6,26.1]	[24.2,26.7]	[13.7,15.2]	[13.7,15.2]	[12.8,14.1]
Fixed (10^6yuan/GW) and variable (10^3yuan/GWh) costs for conversion technologies						
Raw	[13.9,15.3]	[13.4,14.8]	[12.8,14.1]	[14.0,15.4]	[11.2,12.4]	[10.3,11.4]
Hydroelectric	[11.9,13.1]	[11.0,12.2]	[10.9,12.0]	[13.4,14.8]	[13.3,14.7]	[13.1,14.5]
Gas-fired	[554.8,613.2]	[547.2,604.8]	[530.1,585.9]	[64.7,71.5]	[63.9,70.7]	[61.3,67.7]
Photovoltaic	[695.6,768.9]	[668.8,739.2]	[643.2,710.9]	[534.4,590.6]	[402.3,444.7]	[364.0,391.8]
Wind	[82.7,91.4]	[78.3,86.5]	[75.1,83.1]	[112.4,124.2]	[107.1,118.3]	[105.7,116.9]
Biomass	[410.3,453.5]	[401.9,444.3]	[385.7,426.3]	[142.5,157.5]	[132.0,145.8]	[118.8,131.3]

Table.3. Cost of capacity expansion

	Fixed cost			Variable cost		
	t=1	t=2	t=3	t=1	t=2	t=3
Fixed(10^3yuan) and variable (10^3yuan) costs for processing technologies						
Oil refining	[553.1,611.3]	[540.0,596.8]	[526.9,582.4]	[10.5,11.6]	[9.2,10.1]	[7.9,8.7]
Coking	[628.4,694.5]	[615.3,680.0]	[602.2,665.6]	[7.2,8.0]	[7.3,8.2]	[7.5,8.4]
Fixed(10^6/GW) and variable (10^3yuan/GW) costs for conversion technologies						
Raw coal-fired	[73.9,81.7]	[72.4,80.0]	[71.1,78.5]	[4.7,5.2]	[4.6,5.1]	[4.5,5.0]
Hydroelectric	[62.6,69.2]	[61.4,67.8]	[60.1,66.5]	[4.3,4.7]	[3.8,4.2]	[3.7,4.0]
Gas-fired	[233.4,258.0]	[225.6,249.4]	[226.7,250.5]	[1.0,1.1]	[0.9,1.0]	[0.8,0.9]
Photovoltaic	[527.3,582.8]	[507.3,560.7]	[486.4,537.6]	[40.9,45.2]	[38.0,42.0]	[36.6,40.4]
Wind	[243.5,269.1]	[236.3,261.1]	[233.0,257.6]	[7.6,8.4]	[6.8,7.6]	[6.5,7.1]
Biomass	[399.0,441.0]	[380.0,420.0]	[370.5,409.5]	[3.9,4.3]	[3.8,4.2]	[3.3,3.7]

4. Result analysis and discussion

Through solving the aforementioned model, optimized solutions can be obtained.

The optimal energy scheme is analyzed from different aspects, such as energy supply, power supply, pollutant emission control, forest area and system cost.

4.1. Energy supply

Solutions of the energy supply are presented in Fig. 2. It displays the results of energy supply including eight energy types (coal, diesel oil, fuel oil, gasoline, crude oil, LPG, coke and natural gas) and comprises the solutions under different planning periods and *p* levels. Variations in the *p* level correspond to the decision makers' preferences regarding the level of satisfaction in energy supply, i.e. the risk of violating the energy demand constraint. In the Fig. 1(b), the results indicate that any change in *p* levels would result in different supply patterns of diesel oil and fuel oil, while other kinds of energy would keep the same. In detail, the fuel oil supply would increase with the raising of *p* levels. For instance, in period 1, fuel oil supply would increase from 341,750 TJ (p=0.01) to 351,760 TJ (p=0.1). In the Fig. 1(a), the amount of energy supply would increase from period 1 to period 3 under the same *p* level expect for coal and crude oil. For example, coal supply would decrease from 536,590 TJ (period 1) to 469,030 TJ (period 3); natural gas supply would increase from 273,350 TJ (period 1) to 294,590 TJ (period 3). The amount of coal and crude oil would decrease due to their high pollutant emission and the request of pollutant mitigation. The results also indicate that coal would always be one of the largest sources among all energy supplies, however, it will gradually decrease with time. The natural gas supply would be greatly increased, implying that natural gas would be one of the major energy sources in the future. Such an increase is mainly due to the promotion of new energy vehicles from Guangzhou municipal government. Moreover, “13th Five-Year of Guangzhou planning” was proposed to increase the proportion of clean energy consumption. Therefore, the utilization of renewable energy should be encouraged to help the transition to clean energy system.

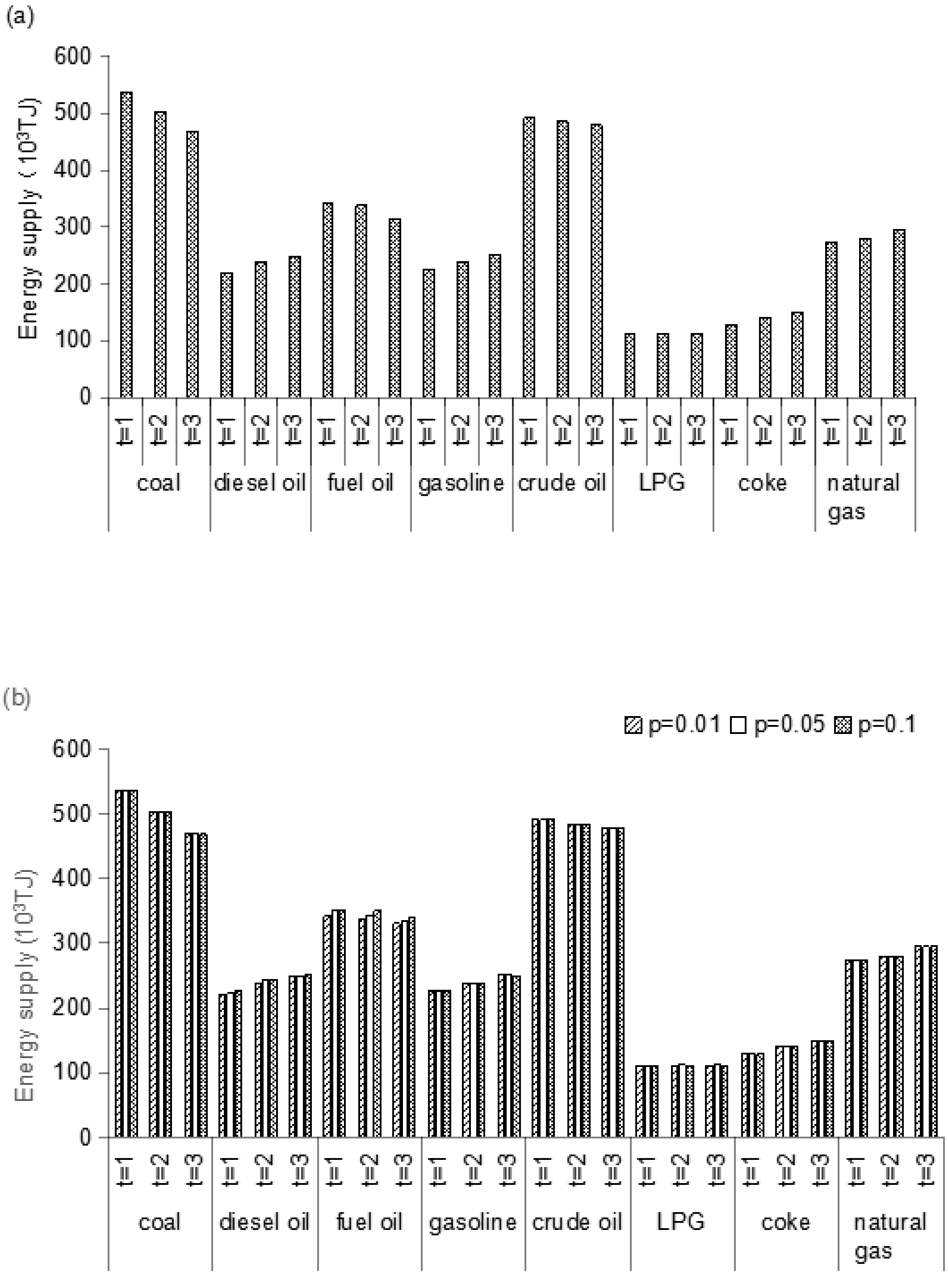
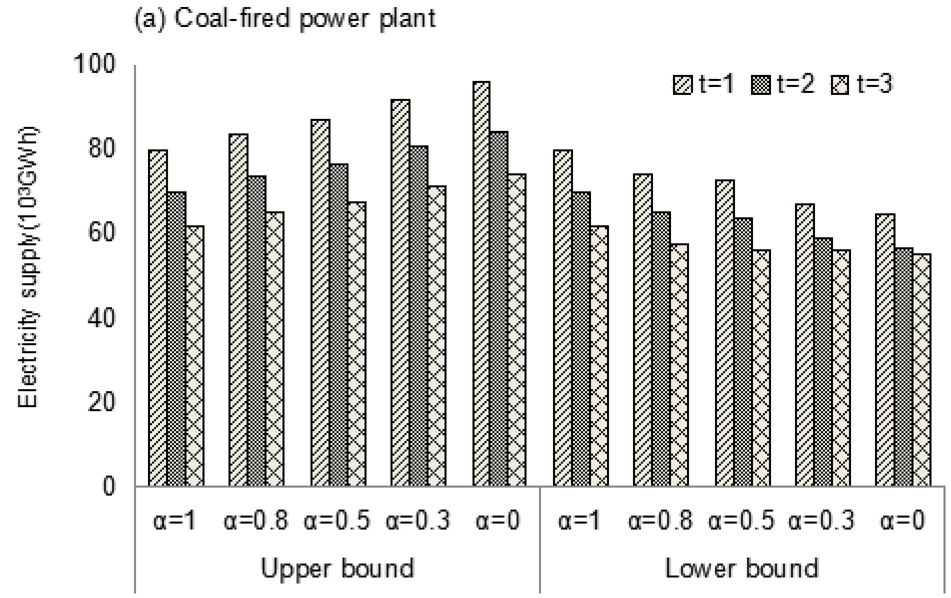


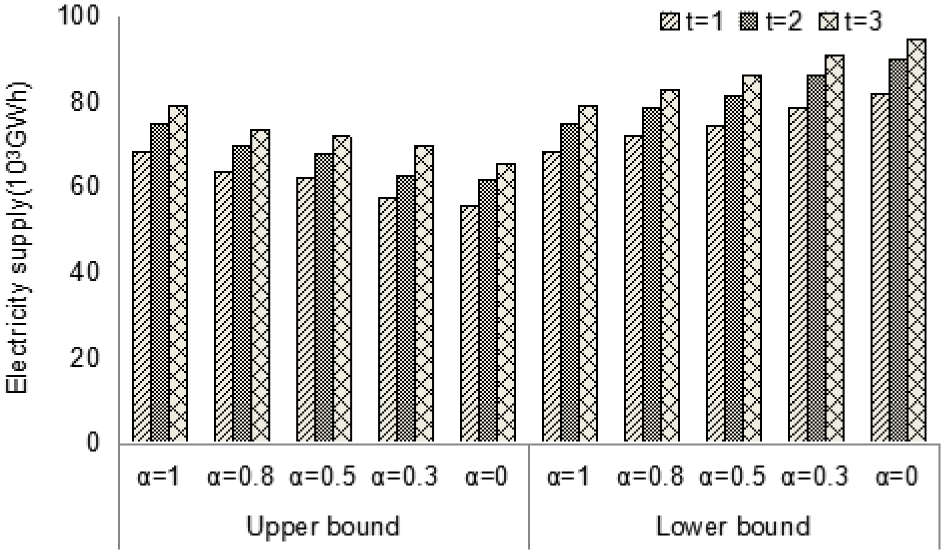
Fig.2 Solutions of energy supply (a) under different planning periods, (b) under different *p* level

4.2. Electricity supply

Solutions of electricity supply under different α-cut levels are presented in Fig. 3. The results show that there is a similar tendency of electricity supply for each conversion technology type under different α-cut levels. As shown in Fig. 3(a), the amount of coal-fired power generation decreases with the growth of time, and in the Fig. 3(b), the natural gas-fired power generation increase with time. Although coal-fired power still accounts for a large proportion of electricity providers, raw materials for coal-fired power generation will decline over time. The electricity production from coal-fired plants would fall due to the high pollutant emission contractions, the shortage of resources and limited raw coal availability. Accordingly, coal-fired equipment expansion will not be expanded in the future. In contrast, the rapid consumption of renewable energy will replace fossil fuel and it can reduce the adverse impact on the environment. In the Fig. 4, Renewable energy (including hydro power, wind power, solar power and biomass power generation) will continue to increase. Such an increase is due to the advantage of clean nature, high efficiency, and safety considerations of renewable energy. For example, hydro power will increase from 2,750 GWh to 3,070 GWh, and the solar power will increase from 8,660 GWh to 9,620 GWh. In the case of rapid growth of renewable energy sources, the expansion is inevitable. As shown in the Table 4, hydro power, wind power, solar power generation and biomass power generation are expanded in the first period, natural gas power generation expansion in the second period.


(a) Coal-fired power plant

（b）Natural gas-fired power plant



(c) Renewable energy power plant

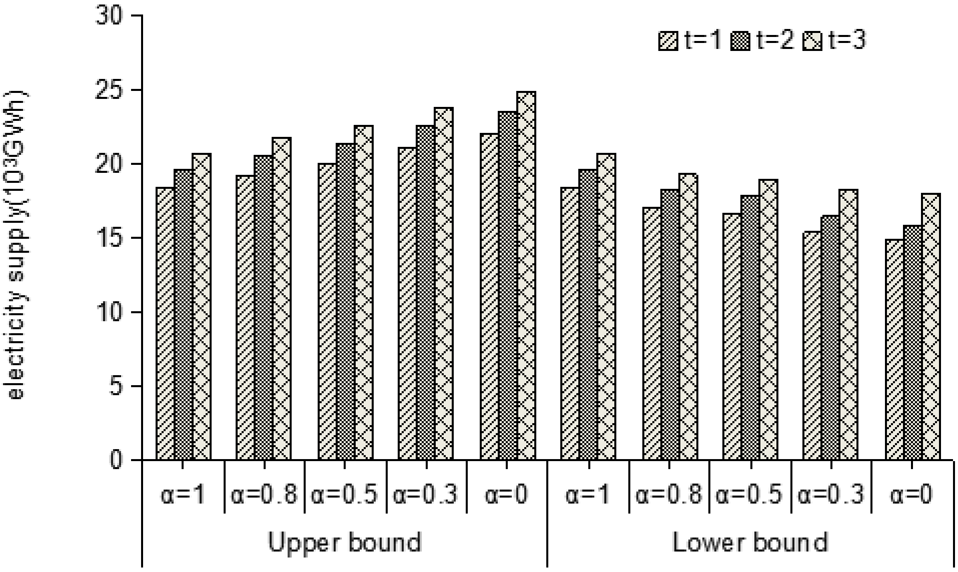


Fig.3. Solutions of all kinds of energy under different α levers

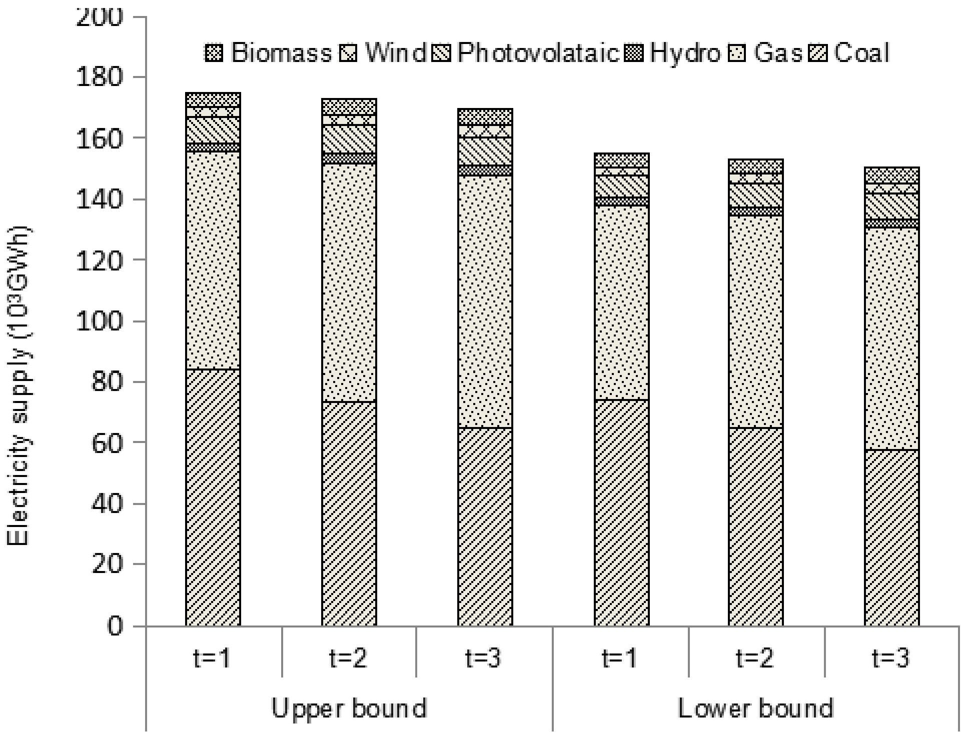


Fig.4. Electricity generation pattern

Table.4. Capacity expansion under different *p* level

	p=0.01			p=0.05			p=0.1		
	t=1	t=2	t=3	t=1	t=2	t=3	t=1	t=2	t=3
Natural gas-fired power (GW)	0	2.3	0	0	2.3	0	0	2.3	0
Hydro power(GW)	0.1	0	0	0.1	0	0	0.1	0	0
Photovoltaic power(GW)	0.05	0	0	0.05	0	0	0.05	0	0
Wind power(GW)	0.2	0	0	0.2	0	0	0.2	0	0
Biomass-fired(GW)	0.05	0	0	0.05	0	0	0.05	0	0

4.3 Pollutant emission control

The energy structure of Guangzhou city, dominated by fossil fuels, has caused serious air pollution, which brings great pressure on air pollution control. Fig.5 (a) shows the results of the processing emission of pollutants and the Fig.5 (b) shows the results of the conversion emission of pollutants, including sulfur dioxide (SO_2), nitrogen oxide (NO_X), and particulate matter (PM_{10}). The results show that with the passage of time, the amount of emitted pollutants will decrease, which may be due to the use of a large number of clean energy and reduce the use of coal. The α-cut level correspond to different risks, and different solutions can be given according to the target. For example, when the α-cut is at the level of 1, the amount of SO_2 emission would decrease from 6,730 tonnes in period 1 to 6,010 tonnes in period 3. Such a decrease may be the reason of the installation of emission reduction facilities in power plants and the increase of renewable energy power plants. Meanwhile, a lower α-cut level would lead to a lower constraint-violation risk, implying a conservative environmental management strategy. On the contrary, a higher α-cut level would correspond to a higher risk of violating the constraint and a higher level of pollutant emission, implying an increased risk of environmental pollution. For example, in period 1, the SO_2 and the NO_X emission would decrease from 16,720 t (α =0 level) to 4,960 t (α =1 level), and 12,610 t (α =0 level) to 6,730 t (α =1 level) , respectively. The α value is closer to 1, the pollutant emissions are less risk, high α-cut level corresponding to a serious constraint violation, which means that the decreased risk of environmental pollution. In the decision making process, the α-cut level will also reflected the preferences of policy makers. When α-cut levels is at level of 0, 0.3, 0.5 0.7 and 1 , the SO_2 emissions would be 38,850 t, 30,720 t, 19,900 t, 18,130 t, 12,200 t in period 1, respectively. The high level of α would be selected if the discharge requirements are strict. Furthermore, the temporal and spatial variations of energy demand and availability may also lead to varied pollution emission. According to the city planning decision makers can choose the corresponding α-cut level and it can also provide more choices and references to decision makers.

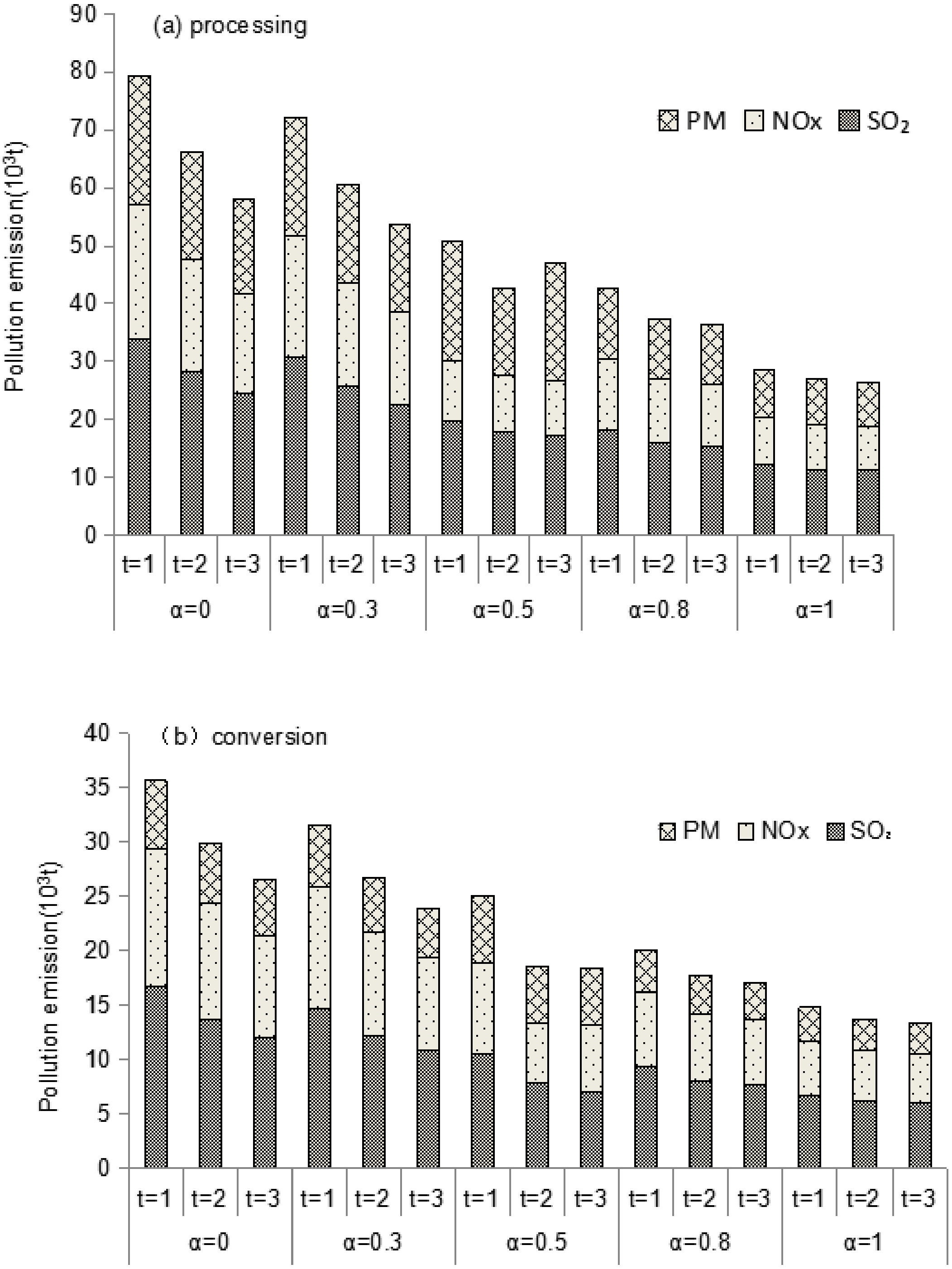
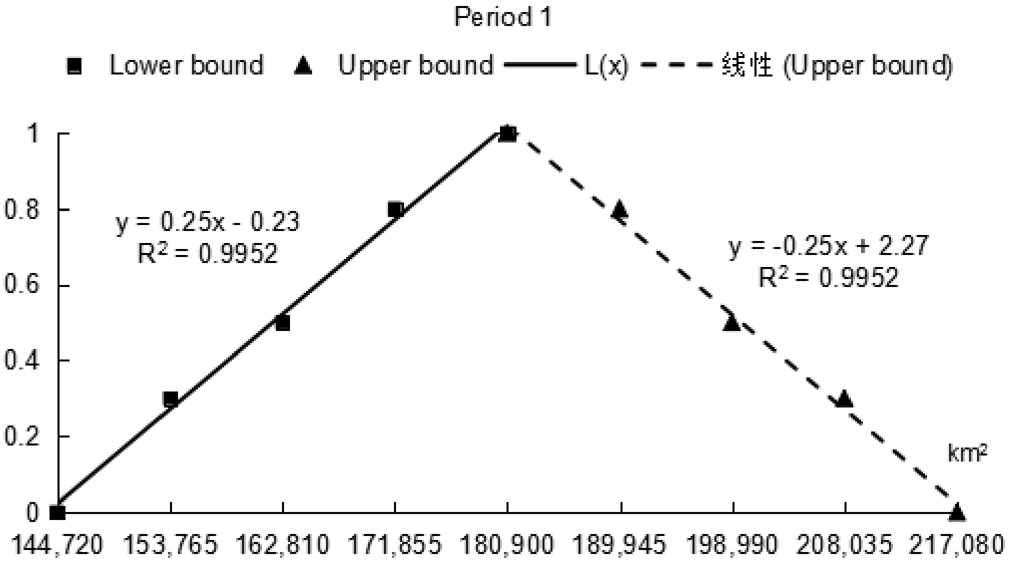


Fig.5. Solutions of pollutant emission (10^3t)

4.4 Forest area and system cost

Forest area represent the abilities of carbon absorption/sink in the ecological systems. Thus, the planting area is optimized for the purpose of carbon mitigation. Fig.6 shows the obtained membership functions of the fuzzy variables of the forest area. The results show that different plausibility degrees of uncertain input would lead to various system benefits. The upper-bound of the objective function value corresponds to favorable conditions, and the lower-bound one is related to the requirements. Correspondingly, in different periods, the number of forests is not the same. At the same level of α, the number of forests is increasing gradually. For example, the forest areas would be increased from 189,000 km^2 (period 1) to 191,916.8 km^2 (period 3). There is a trend of growth because forests can absorb carbon dioxide and reduce the greenhouse effects. Fig.7 shows the objective function value under different levels, which can be well fitted through linear regression. Hence, given the range of any target function, it can get the different α-cut level and get the optimal solutions. Moreover, when the preferred α value is predetermined by the decision makers, the energy selections can also be obtained directly from the resulting fuzzy membership function. For example, if decision makers tend to ecological forest conservation, you can choose a ɑ-cut level of 0.8. While if the finance is deficit and not enough to support the expansion of forest, decision makers can considered a low level such as 0. When α level is closer to 1, the decision is narrower, and the ɑ level is closer to 0, the decision is wider. The solution has provided alternatives with different levels of accuracies of input information, thus the decision makers can select the corresponding solutions according to their capabilities of risk tolerance.



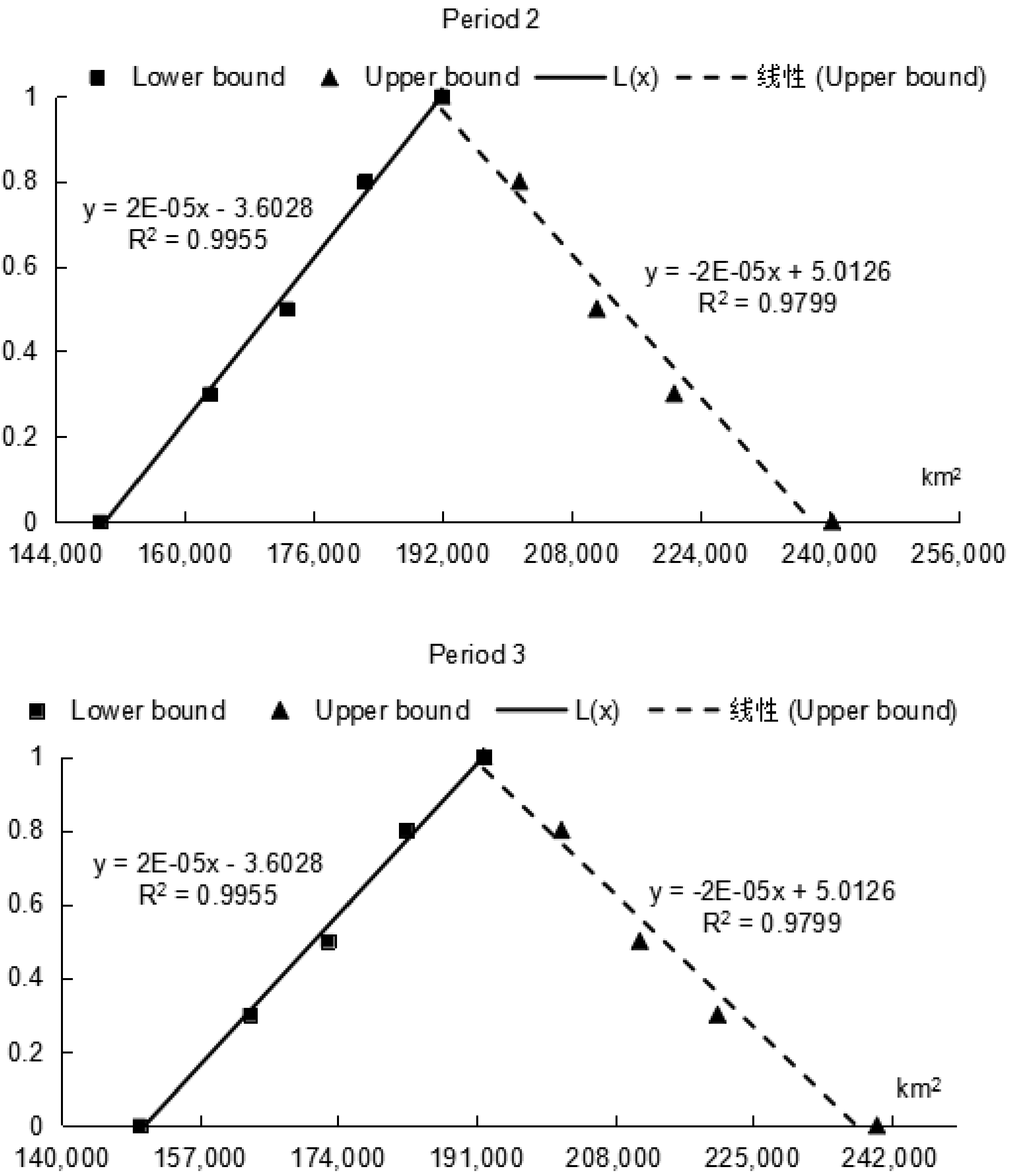


Fig.6. Membership functions of the forest coverage (km^2)

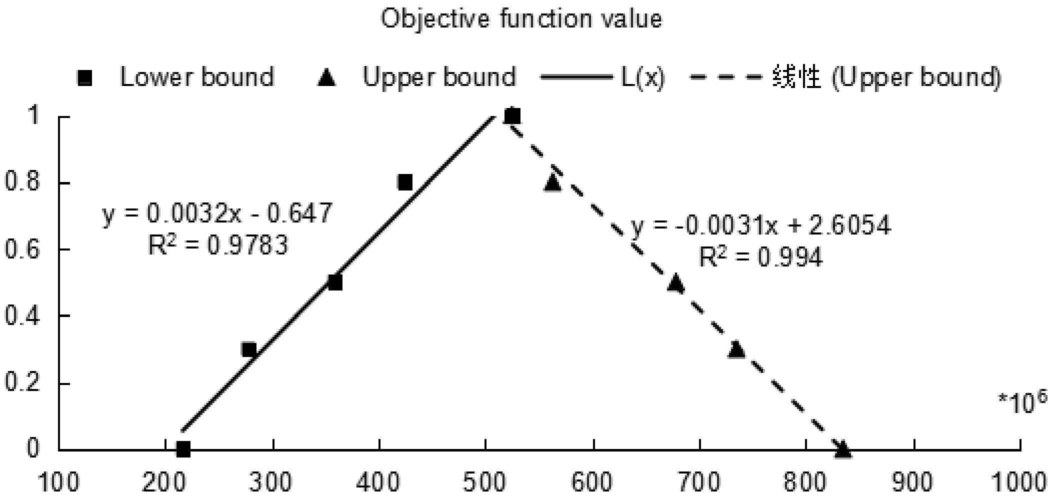


Fig.7. Membership function of the objective function

5. Conclusions

In this study, a GFCCP (generalized fuzzy chance-constrained programming) method has been developed for supporting energy system planning in Guangzhou under multiple uncertainties. In GFCCP, the parameter uncertainty expressed as generalized fuzzy sets and probabilistic distribution can be effectively solved. Through GFCCP model, solutions of energy supply, energy allocation, power generation, capacity expansion, air pollutant emission reduction, forest planning, system cost under different levels of α-cut are obtained considering the constraint violation risk. The results showed that: (i) the consumption of coal will decline year by year, while natural gas will become the main source of energy supply to the city in the future; (ii) the power structure of the city tends to be from coal into clean energy (e.g., solar, wind, hydro and other renewable energy), and the city’s energy supply security is enhanced by stimulating the utilization of renewable energy; (iii) The rational use of ecological land is of great significance, forests can absorb carbon dioxide and play a positive role in reducing the greenhouse effect. The results of the study will help managers to adjust the city’s current energy structure, improve energy supply security, and make decisions according to different preferences between system cost and default risk.

The developed GFCCP can handle multifarious fuzzy sets and fuzzy random variables. This is the first attempt to apply GFCCP method to the energy systems planning of Guangzhou. This research is aimed at the planning model of the typical urban energy system. Because there is a lot of uncertainty in the energy system, we use generalized fuzzy chance constrained programming method to solve it. The uncertainties considered in the model, as well as the components of the model, can also be applied to other areas. Results obtained demonstrate that GFCCP can not only deal with uncertainty expressed by generalized fuzzy sets, but also effectively handle uncertainty in terms of probabilistic distribution, and GFCCP can also generate solutions presented as fuzzy sets, which can provide ranges and possibilistic distributions, and these ambiguous solutions will effectively help the decision makers to analyze the trade-off between system benefit and process reliability. However, it focused primarily on uncertainties within an LP framework. It lacks the ability to handle nonlinear constraints. Thus, further improvement in the GFCCP are desired to enhance its capability in treating nonlinearity within the optimization framework.

Acknowledgements

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Appendix

Subscript

t	planning period, with t=1 for 2017-2019, t=2 for 2020-2022, t=3 for 2023-2025.
f	system cost (10^6)
i	imported energy type and energy types transferred from other provinces, with i=1 for coal, i=2 for diesel oil, i=3 for fuel oil, i=4 for gasoline, i=5 for crude oil, i=6 for liquefied petroleum gas(LPG), i=7 for coke, i=8 for natural gas.
j	exported energy type and types of energy transferred in this province, with j=1 for coal, j=2 for diesel oil, j=3 for fuel oil, j=4 for gasoline, j=5 for crude oil, j=6 for liquefied petroleum gas(LPG), j=7 for coke, j=8 for natural gas.
m	processing technology type, with m=1 for coking, m=2 for oil refining.
n	conversion technology type, with n=1 for coal-fired power, n=2 for hydroelectric power, n=3 for gas-fired power, n=4 for photovolataic power, n=5 for wind power, n=6 for biomass power.
l	air pollution type, with l=1 for SO_2, l=2 for NO_X, l=3 for PM.

Decision variable

NCL_{it}	purchase amount of energy type i in period t (10^3TJ)
WCL_{it}	purchase amount of energy type i transferred from other provinces in period t (10^3TJ)
CXL_{jt}	selling amount of energy type j in period t (10^3TJ)
BXL_{jt}	selling amount of energy type j transferred from our province in period t (10^3TJ)
JCL_{mt}	generation amount of energy processing technology m in period t (TJ)
ZCL_{nt}	generation amount of energy conversion technology n in period t (10^3GWh)
SA_t	forest area in period t (km^2)
JL_{mt}	amount of energy processing technology m in period t (TJ)
DDL_t	amount of import electric power in period t (GWh)

$JSFK_{mkt}$	binary variable for identifying whether or not a capacity expansion action of energy processing technology m needs to be undertaken in period t
$ZSFK_{nkt}$	binary variable for identifying whether or not a capacity expansion action of energy conversion technology n need to be undertaken in period t

Parameters

JCB_{it}	purchase cost of energy type i in period t (10^3/TJ)
WCB_{it}	purchase cost of energy type i transferred from other provinces in period t (10^3/TJ)
CXE_{jt}	selling cost of energy type j in period t (10^3/TJ)
BXE_{jt}	selling cost of energy type j transferred from our province in period t (10^3/TJ)
JGC_{mt}	fixed operation and maintenance cost of energy processing technology m in period t (10^3/TJ)
JN_{mt}	capacity of energy processing technology m in period t (10^3TJ)
JKC_{mt}	variable operation and maintenance cost of energy processing technology m in period t (10^3/TJ)
ZGC_{nt}	fixed operation and maintance cost of energy conversion technology n in period t (10^6/GW)
ZN_{nt}	capacity of energy conversion technology n in period t (GW)
ZKC_{nt}	variable operation and maintance cost of energy conversion technology n in period t (10^3/GWh)
JKN_{mt}	expanded capacity of energy processing technology m in period t(TJ)
$ZCKC_{nt}$	variable cost of capacity expansion for energy conversion technology n in period t (10^3/GW)
ZKN_{nt}	expanded capacity of energy conversion technology n in period t(GW)
$JWPL_{lmt}$	unit air-pollution type l emission of energy processing technology m in period t(t/TJ)
$JWHX_{lmt}$	air-pollution type l mitigation efficiency of energy processing technology m in period t

$JWPC_{lmt}$	air-pollutant type l emission cost of energy processing technology m in period t(10^3/t)
$ZWPL_{\ln t}$	unit air-pollution type l emission of energy conversion technology n in period t(t/GWh)
$ZWHX_{\ln t}$	air-pollution type l mitigation efficiency of energy conversion technology n in period t
$ZWPC_{\ln t}$	air-pollutant type l emission cost of energy conversion technology n in period t(10^3/t)
JJC_{mt}	CO_2 mitigation cost of energy processing technology m in period t (10^3/TJ)
ZJC_{nt}	CO_2 mitigation cost of energy conversion technology n in period t ((10^3/GWh)
b_t	imported electric quantity ratio in period t
a_{mt}	energy processing efficiency m in period t
FP_{it}	production ratio of energy type i in period t
ZX_{it}	total demand of energy type i in period t (10^3TJ)
DZL_t	total demand of electricity in period t (10^3GWh)
SSL_t	loss rate of electricity transmission in period t
KNL_{it}	available renewable energy consumption of type i in period t (10^3TJ)
$JCGC_{mt}$	fixed cost of capacity expansion for energy processing technology m in period t (10^3)
$ZCGC_{nt}$	variable cost of capacity expansion for energy conversion technology n in period t (10^3)
$KZSL_{nt}$	renewable energy consumption in period t (10^3TJ)
$DZCL_{\ln t}$	amount of carbon dioxide produced by unit power generation n in period t (t/GWh)
DJL_{lmt}	amount of pollutant discharged by unit processing in period t (t/TJ)
YGC_t	cost of forest management and protection in period t (10^3/km^2)
DJY_t	forest ecological benefits in period t (10^3/km^2)
PAE_{lt}	total emission of pollutants type l in period t (t)
CE_t	total carbon dioxide emissions in period t (t)

DST_t	elimination of carbon dioxide by unit forest area in period t (t/km^2)
$SA_{\min}$	minimum forest area in period t (km^2)
$SA_{\max}$	maximum forest area in period t (km^2)
DJJ_t	cost of electric power in period t (10^3/TJ)
$FDXL_{nt}$	unit of energy per unit generation amount of energy conversion technology n in period t (TJ/GWh)
PEU_{nt}	the least amount of electricity generated by each generation of power generation technology n in period t (GWh)
$MDDL_t$	Minimum power imports in period t (GWh)

References

[1] Elmitwally A, Eladl A. Planning of multi-type FACTS devices in restructured power systems with wind generation[J]. International Journal of Electrical Power & Energy Systems, 2016, 77:33-42.

[2] Lin B, Li J. Analyzing cost of grid-connection of renewable energy development in China[J]. Renewable & Sustainable Energy Reviews, 2015, 50:1373-1382.

[3] Lee J H. Energy supply planning and supply chain optimization under uncertainty ☆[J]. Journal of Process Control, 2014, 24(2):323-331.

[4] Suganthi L, Iniyan S, Samuel AA. Applications of fuzzy logic in renewable energy systems – a review. Renew Sustain Energy Rev 2015,48:585–607.

[5] Huh S Y, Lee J, Shin J. The economic value of South Korea′s renewable energy policies (RPS, RFS, and RHO): A contingent valuation study[J]. Renewable & Sustainable Energy Reviews, 2015, 50:64-72.

[6] Zhang X, Duncan I J, Huang G, et al. Identification of management strategies for CO_2, capture and sequestration under uncertainty through inexact modeling[J]. Applied Energy, 2014, 113(6):310-7.

[7] Fu Z H, Xie Y L, Li W, et al. An inexact multi-objective programming model for an economy-energy-environment system under uncertainty: A case study of Urumqi, China[J]. Energy, 2017, 126:165-178.

[8] Khiareddine A, Salah C B, Rekioua D, et al. Sizing methodology for hybrid photovoltaic /wind/ hydrogen/battery integrated to energy management strategy for pumping system[J]. Energy, 2018, 153.

[9] Alipour M, Hafezi R, Ervural B, et al. Long-term policy evaluation: Application of a new robust decision framework for Iran’s energy exports security[J]. Energy, 2018.

[10] Lu W T, Dai C, Fu Z H, et al. An interval-fuzzy possibilistic programming model to optimize China energy management system with CO_2, emission constraint[J]. Energy, 2018, 142:1023-1039.

[11] Huang G H. A hybrid inexact-stochastic water management model[J]. European Journal of Operational Research, 1998, 107(1):137-158.

[12] Nematian J. An Extended Two-stage Stochastic Programming Approach for Water Resources Management under Uncertainty[J]. 2015, 27(2).

[13] Tong L I. Uncertainty Assessment of Non-normal Emission Estimates Using Non-Parametric Bootstrap Confidence Intervals[J]. Journal of Environmental Informatics, 2017, 28(1).

[14] Huang G H, Loucks D P. An Inexact Two-stage Stochastic Programming Model for Water Resources Management under Uncertainty[J]. Civil Engineering Systems, 2000, 17(2):95-118.

[14] Li Y P, Huang G H, Nie S L, et al. Inexact multistage stochastic integer programming for water resources management under uncertainty[J]. Journal of Environmental Management, 2008, 88(1):93.

[15] Zhu Y, Li Y P, Huang G H. Planning municipal-scale energy systems under functional interval uncertainties[J]. Renewable Energy, 2014, 39(1):71-84.

[16] Jin S W, Li Y P, Huang G H. An interactive optimization model for energy systems planning associated with clean—energy development under uncertainty[J]. International Journal of Energy Research, 2017, 41(4).

[17] Liu Y, Li H, Chen Y. Development of a single-level optimization model for energy planning—A

case study of Shanxi, China[C]// American Institute of Physics Conference Series. American Institute of Physics Conference Series, 2017:040007.

[18] Fan Y, Huang G, Veawab A. A generalized fuzzy linear programming approach for environmental management problem under uncertainty[J]. Journal of the Air & Waste Management Association, 2012, 62(1):72.

[19] You L, Li Y P, Huang G H, et al. Modeling regional ecosystem development under uncertainty—A case study for New Binhai District of Tianjin[J]. Ecological Modelling, 2014, 288(5):127-142.

[20] Liu B. Fuzzy random chance-constrained programming[J]. Fuzzy Systems IEEE Transactions on, 2001, 9(5):713-720.

[21] Suo C, Li Y P, Wang C X, et al. A type-2 fuzzy chance-constrained programming method for planning Shanghai’s energy system[J]. International Journal of Electrical Power & Energy Systems, 2017, 90:37-53.

[22] Nie S, Huang C Z, Huang G H, et al. Planning renewable energy in electric power system for sustainable development under uncertainty—A case study of Beijing[J]. Applied Energy, 2016, 162:772-786.

[23] Fan Y R, Huang G H, Yang A L. Generalized fuzzy linear programming for decision making under uncertainty: Feasibility of fuzzy solutions and solving approach[J]. Information Sciences, 2013, 241(12):12-27.

[24] Li Y P, Huang G H. Fuzzy-stochastic-based violation analysis method for planning water resources management systems with uncertain information[J]. Information Sciences, 2009, 179(24):4261-4276.

[25] Anderson L. A Risk-Averse Optimization Model for Unit Commitment Problems[C]// Hawaii International Conference on System Sciences. IEEE, 2015:2577-2585.

[26] Liu Z, Huang G, Li W. An inexact stochasticâ€ “fuzzy jointed chance-constrained programming for regional energy system management under uncertainty[J]. Engineering Optimization, 2015, 47(6):788-804.

[27] Roubens M, Jr J T. Comparison of methodologies for fuzzy and stochastic multi-objective programming[J]. Fuzzy Sets & Systems, 1991, 42(1):119-132.

[28] Fan Y, Huang G, Veawab A. A generalized fuzzy linear programming approach for environmental management problem under uncertainty[J]. Journal of the Air & Waste Management Association, 2012, 62(1):72.

[29] Cai Y P, Tan Q, Huang G H, et al. Community-scale renewable energy systems planning under uncertainty—An interval chance-constrained programming approach[J]. Renewable & Sustainable Energy Reviews, 2009, 13(4):721-735.

[30] Huang G, Baetz B W, Patry G G. A Grey Linear Programming Approach for Municipal Solid Waste Management Planning under Uncertainty[J]. Civil Engineering Systems, 1992, 9(4):319-335.

[31] GSYB: Guangzhou's statistical year book. Guangzhou Statistic Bureau. Guangzhou, China; 2015. http://210.72.4.52/gzStat1/chaxun/njsj.jsp

[32] Thirteenth five year plan of energy development in Guangzhou, China, 2017. http://www.china-nengyuan.com/news/117134.html.