A copula-based fuzzy interval-random programming approach for planning water-energy nexus system under uncertainty

L. Yu[1*], Y. Xiao[2], S. Jiang[3*], Y.P. Li[4], Y.R. Fan[5], G.H. Huang[6], J. Lv[7], Q.T. Zuo[8], F.Q. Wang[9]

[1*] (Corresponding Author) School of Water Conservancy Engineering, Zhengzhou University, Zhengzhou 450001, China; Zhengzhou Key Laboratory of Water Resource and Environment, Zhengzhou, 450001, China; Henan Key Laboratory of Groundwater Pollution Prevention and Rehabilitation, Zhengzhou, 450001, China; E-mail: yulei2018@zzu.edu.cn

[2] School of Water Conservancy Engineering, Zhengzhou University, Zhengzhou 450001, China; E-mail: xiaoyaocs@163.com

[3*] (Corresponding Author) Department of water resources, China Institute of Water Resources and Hydropower Research, Beijing 100038, China; E-mail: jiangs@iwhr.com

[4] School of Environment, Beijing Normal University, Beijing 100875, China; E-mail: yongping.li@iseis.org

[5] Department of Civil and Environmental Engineering, Brunel University London, Uxbridge, UB8 3PH, United Kingdom; E-mail: yurui.fan@gmail.com

[6] Institute for Energy, Environment and Sustainable Communities, University of Regina, Regina, Sask. S4S 7H9, Canada; E-mail: gordon.huang@uregina.ca

[7] Sino-Canada Energy and Environmental Research Center, North China Electric Power University, Beijing 102206, China; E-mail: 291697439@qq.com

[8] School of Water Conservancy Engineering, Zhengzhou University, Zhengzhou 450001, China; E-mail: zuoqt@zzu.edu.cn

[9] Department of Water Conservancy Engineering, North China University of Water Resources and Electric Power, Zhengzhou 450046, China; E-mail: wangfuqiang@ncwu.edu.cn

Abstract

Water and energy are closely linked and restrict each other, which has become major restraints to urban development associated with constricted water availability, increased electricity demand and limited environmental capacity. In this study, a copula-based fuzzy interval-random programming method is proposed through integration of copula-based random programming, interval-parameter programming and fuzzy possibilistic programming. It can both handle random, interval and fuzzy information and reflect system joint-risk existed in the water-energy nexus system of Henan Province, China. A class of copulas associated with different water resource-availability and electricity-consumption scenarios as well as various uncertainties are examined. Results disclose that: a) uncertainties and scenarios employed to water resources, electricity demand and other module parameters can generate prominent impacts on the future water-energy nexus system; b) the percentage of electricity by coal-fired power can decrease by [1.8, 2.6] % under low water-availability scenario compared to high water-availability scenario. Findings can provide optimal electricity-supply schemes under the conflicts among economic objective, water resources shortage and electricity demand, as well as environmental requirement.

Keywords: copula, interaction, joint risk, uncertainty, water-energy nexus system

1. Introduction

1.1 Importance

Water and energy, the world's two most critical resources, are gaining international attention from both the general public and the academia [1]. Water and energy are closely linked. The supply, transportation and treatment of water resources need to consume a large amount of energy, while the whole process of energy production from mineral exploitation to electricity generation needs to be completed under the action of water cleaning, cooling and conduction [2]. Water and energy are interdependent and restrict each other, which has become major restraints to urban development [3].China, a largest developing country around the world, occupies 21% of the world's energy consumption and holds 6% of the global fresh water sources [4]. The contradictions among water, energy, air pollution and carbon dioxide (CO_2) emissions are increasingly deteriorative. Moreover, the primary energy bases in China are among the most water-stressed area of the country [5]. Such mismatched geographical space further aggravates the challenge between water shortage and energy security. Although several polices such as "3 Red lines" and "Water allocation plan for coal bases" were enacted to reduce water utilization, improve water efficiency and reduce sewage water discharges in the coal sector, particularly for further managing future coal-fired power plants in water-scarce regions [6]. However, in real-world water-energy nexus (WEN) problems, water and energy resources are associated with social, economic, managerial and environmental limitations [7]. Above of which force researchers to propose effective strategies toward the energy system's water utilization in a mutually-beneficial manner between economic development and environmental mitigation.

1.2 Literature review

Previously, numerous studies were focused on quantitatively analyzing WEN system. For example, Al-Ansari et al. [8] adopted a life cycle assessment (LCA) approach to assess the nexus of water-energy-food (WEF) in food production systems. Wang and Chen [9] developed a multi-regional network model for planning the WEN of Beijing-Tianjin-Hebei urban agglomeration. Chhipi-Shrestha et al. [10] used a system dynamic modelling (SDM) to recognize key factors for the urban water system in Penticton. Khan et al. [11] formulated an integrated agent-based modelling ABM-SWAT (soil and water-assessment tool) model for analyzing the water-energy-food-environment (WEFE) nexus system management in transboundary river basins. Summarily, the above studies are mainly focused on dealing with WEN problems when their system components were deterministic. However, some coefficients are not obtained as deterministic due to the inaccuracy of empirical observations and estimations [12]. Thus, it is of indispensability to exploit more robust optimization techiques for planning WEN corresponding to the associated complexities and uncertainties [13].

Recently, lots of efforts were made in WEN for dealing with uncertainties such as integrated energy system modelling (IESM), multi-objective programming (MOP), two-level programming (TLP), system dynamics approach (SDA). For example, Zhang and Vesselinov [14] proposed a bi-level model for handling the tradeoffs in WEN problems. Bieber et al. [15] developed an integrated modelling for the WEF nexus system, where ABM was used for simulating varied resource demands and scenario-based approaches were used for presenting different policies. Li et al. [16] used an incorporated multi-objective programming method to planning the agricultural WEF, where contradictions among water, energy, food and land are handled. Feng et al. [17] used the system dynamics approach for modeling the nexus across water, power and environment in Hehuang Region, China. In general, the above studies mainly focused on handling WEN tradeoffs through using the modeled scenarios among different policies or varied views of decision makers, and overall satisfaction of the two-level decision makers [18]. However, few of them are specialized in analyzing the intricate and complex interactions of the WEN system. For a real-world WEN system, it includes two subsystems (water subsystem and energy subsystem), and each contains multiple layers and components. Every component in each subsystem can result in changed influence on the other subsystem and pose joint shortage risk between water and energy [19]. Copula approach has its effectiveness in reflecting joint-violation risk through modeling multivariate joint distributions [20].

1.3 Contribution

This study aims to propose a copula-based fuzzy interval-random programming (CFIP) approach for multi-uncertainty reflection by combining copula-based random programming (CRP), interval-parameter programming (IPP) and fuzzy possibilistic programming (FPP). Compared to the deterministic quantitatively analysis methods in Al-Ansari et al. [8], Wang and Chen [9], Chhipi-Shrestha et al. [10] and Khan et al. [11], CFIP can handle complexities and uncertainties existing in WEN management problems. In comparison with the inexact optimization methods in Zhang and Vesselinov [14], Bieber et al. [15], Li et al. [16], and Feng et al. [17], CFIP can not only deal with uncertainties presented by the interval and fuzzy information but also tackle the random water resources availability and electricity demand as well as the correlative system joint-risk. Summarily, CFIP combines the superiority of CRP, IPP and FPP into one framework, which can efficaciously: (a) deal with the uncertainties expressed as random variables, interval values and fuzzy sets as well as their combinations (i.e. interval-fuzzy modulus and interval-random variables); (b) reveal the water-shortage risk, electricity-shortage risk as their correlated joint-shortage risk. Then, a CFIP-WEN model is developed and then applied to the WEN system of Henan Province, China. In the CFIP-WEN model, four classes of copulas (i.e. Clayton, Frank, Gumbel and Student's t copulas), five scenarios with different groups of water resources availability and electricity consumption, four λ levels corresponding to decision makers' different necessity degrees of the system cost are considered. Results will help decision makers: (a) identify the desired electricity-supply patterns under the conflicts among economic objective, water resources shortage and electricity demand as well as environmental requirement; (b) analyze interactions between water resources availability and electricity consumption, and disclose their joint risk on WEN system associated with different scenarios.

2. Methodology

CRP has advantages of capturing the dependence of bivariate or multivariate random variables and binding disparate univariate marginal distributions together through constructing their joint distribution based on a copula function [21]. According to Charnes and Cooper [22], Chen et al. [23], Simic and Dabic-Ostojic [24], a generic CRP model can be depicted as

$$\text{Min } E = \sum_{j=1}^{n} c_j x_j \tag{1a}$$

subject to:

$$\sum_{j=1}^{n} a_{ij} x_j \leq b_i^{p_i}, \; i = 1, 2, ..., k \tag{1b}$$

$$C(1 - p_1, 1 - p_2, ..., 1 - p_k) = 1 - p \tag{1c}$$

$$\sum_{j=1}^{n} a_{ij} x_j \leq b_i, \; i = k+1, k+2, ..., m \tag{1d}$$

$$x_j \geq 0, \; j = 1, 2, ..., n \tag{1e}$$

where x_j are decision variables; a_{ij} and b_i are coefficients; $b_i^{p_i}$ are random variables; C is the determinate copula; p_i $(i = 1, 2, ..., k)$ are constraint-violation levels; $b_i^{p_i} = F_i^{-1}(p_i)$.

For a real-world WEN system, some economic parameters are affected by the socio-economic, political, legislation and technical factors, which can hard to be achieved as stochastic variables but can be presented as interval values through using the IPP technique [25]. Some imprecise data can rarely be achieved as randomness and interval but can be presented by fuzzy sets [26]. Through introducing IPP and FPP into CRP, a CFIP model can be formulated as:

$$\text{Min } \underset{\sim}{E}^{\pm} = \sum_{j=1}^{n} \underset{\sim}{c}_j^{\pm} x_j^{\pm} \tag{2a}$$

subject to:

$$\sum_{j=1}^{n} a_{ij}^{\pm} x_j^{\pm} \leq b_i^{(p_i)\pm}, \; i = 1, 2, ..., k \tag{2b}$$

$$C(1 - p_1, 1 - p_2, ..., 1 - p_k) = 1 - p \tag{2c}$$

$$\sum_{j=1}^{n} a_{ij}^{\pm} x_j^{\pm} \leq b_i^{\pm}, \; i = k+1, k+2, ..., m \tag{2d}$$

$$x_j^{\pm} \geq 0, \; j = 1, 2, ..., n \tag{2e}$$

where $a_{ij}^{\pm} \in \{R^{\pm}\}^{m \times n}, b_i^{\pm} \in \{R^{\pm}\}^{m \times 1}, \underset{\sim}{c}_j^{\pm} \in \{R^{\pm}\}^{1 \times n}, x_j^{\pm} \in \{R^{\pm}\}^{n \times 1}$; $R^{\pm}$ mean interval numbers; $\underset{\sim}{c}_j^{\pm}$ represent fuzzy-boundary intervals. Based on Inuiguchi and Ramik [27], Model (2) can be converted into:

$$\text{Min } \underset{\sim}{E}^{\pm} = \left(\sum_{j=1}^{k} c_j^{c\pm} x_j^{\pm} + \sum_{j=1}^{k} \lambda \varpi_j \mid x_j^{\pm} \mid + \sum_{j=k+1}^{n} c_j^{'c\pm} x_j^{\pm} + \sum_{j=k+1}^{n} \lambda \varpi_j^{'} \mid x_j^{\pm} \mid \right) \tag{3a}$$

subject to:

$$\sum_{j=1}^{l} a_{ij}^{\pm} x_j^{\pm} + \sum_{j=l+1}^{n} a_{ij}^{\pm} x_j^{\pm} \le b_i^{(p_i)\pm}, i = 1, 2, ..., k \tag{3b}$$

$$C(1-p_1, 1-p_2, ..., 1-p_k) = 1-p \tag{3c}$$

$$\sum_{j=1}^{l} a_{ij}^{\pm} x_j^{\pm} + \sum_{j=l+1}^{n} a_{ij}^{\pm} x_j^{\pm} \le b_i^{\pm}, i = k+1, k+2, ..., m \tag{3d}$$

$$x_j^{\pm} \ge 0, \ j = 1, 2, ..., n \tag{3e}$$

where λ means p-necessity level [28]. In this study, two-step method (TSM) is used for obtaining interval values of the CFIP model (i.e. $f_{\text{opt}}^{\pm} = [f_{\text{opt}}^{-}, f_{\text{opt}}^{+}]$ and $x_{\text{opt}}^{\pm} = [x_{\text{opt}}^{-}, x_{\text{opt}}^{+}]$) under each p level and each λ level [29].

3. Case Study

Henan Province sits in the central China and covers an area of 167 × 10^3 km^2. It consists of 17 prefectural-level cities and 1 city administrated by province, as shown in Figure 1. In 2017, the gross domestic product (GDP) and total population of Henan reached to RMB¥ 4,498.82 billion and 108.53 million, respectively. Most rivers in Henan originate from mountainous areas in the west, northwest and southeast, among which 560 rivers covering an area of more than 100 km^2. The annual average amounts of water resources reached 40.35 billion m^3, ranking 19th in China. However, the per capita water resources were about 383 m^3, merely accounting for one-fifth of the national average. The limited water resources and increased water demand are increasingly restricting the sustainable development of Henan Province accompanied with anticipated climate change [30].

Place Figure 1 here

As a primary agricultural province, agriculture occupies the primary role in the whole water use, followed by the industry, consumption and ecological protection sectors (Figure 2).For Henan Province, several electricity-conversion technologies such as conventional thermal plants (coal-fired power and nature gas-fired power) and renewable-energy based power plants (hydropower, wind, solar and biomass power) are mainly used for satisfying the local electricity demand. Simultaneously, the conversion processes of these facilities also need water in cooling, steam generation, desulfurization and cleaning. In this study, the modeling parameters are presented as interval values, probability distributions, fuzzy sets as well as their correlated dual uncertainties (i.e. interval-fuzzy modulus and interval-random variables). For example, the correlative water-consumption is subjected to a range of factors (i.e. electricity conversion type, cooling mode, as well as other weather conditions) [4]. The pollutant-emission coefficients and other technical parameters (i.e. residual capacity, capacity expansion, service time, energy consumption rate and power consumption rate) are associated with series of factors such as the energy resources type, energy quality, combustion condition and operation condition, as well as other weather conditions [31]. Thus the correlative water-consumption parameters, pollutant-emission coefficients and other technical parameters are expressed as intervals. Economic coefficients which are closely related to the volatility of interest rates, inflation rates and other factors (i.e., energy price, labor fee, and operation condition) are presented as interval-fuzzy modulus with known fuzzy possibility distributions [32]. Water resources availability and electricity demand which are affected by meteorologic, hydrologic and sociometric conditions are presented as interval-random variables [33].

Place Figure 2

Based on the CFIP method, a provincial-scale CFIP-WEN model is formulated for the purpose of minimizing the system cost, which consists of cost of water resources, energy resources, electricity-generation, -import and -transmission as well as contamination controlling. For example, for a real-world WEN system planning issues, the cost of water resources for electricity generation mainly consists of the processes of cooling, boiling and desulfurization as well as others [32]. Energy import cost includes the cost of importing local and adjacent energies during the conversion activities such as the purchase price of energy resources, workers' wage, truck rental fees and the cost for energy transport losses [34]. The electricity-generation cost always covers a wide range which including unit start-up cost, workers' wage, equipment-maintenance cost and taxation expense. The investment for expanding electricity-conversion technologies such as finance investment, labor fee, equipment maintenance and operation cost, as well as taxation expense [31]. And the pollutant and CO_2 treatment costs can be calculated in terms of the associated emission rates and the unit cost of environmental facilities under various process activities [35]. Therefore, the objective function is:

$$
\begin{aligned}
\text{Min } \underset{\sim}{E}^{\pm} = {} & \overbrace{\sum_{k=1}^{2}\sum_{t=1}^{6} EGA_{k,t}^{\pm}\times\left(\underset{\sim}{CCW}_{k,t}^{\pm}\times CW_{k,t}^{\pm}+\underset{\sim}{CBW}_{k,t}^{\pm}\times BW_{k,t}^{\pm}+\underset{\sim}{CDW}_{k,t}^{\pm}\times DW_{k,t}^{\pm}\right)+\sum_{k=3}^{6}\sum_{t=1}^{6} EGA_{k,t}^{\pm}\times \underset{\sim}{COW}_{k,t}^{\pm}\times OW_{k,t}^{\pm}}^{\text{Cost of water resource for electricity generation}} \\
& + \underbrace{\sum_{k=1}^{2}\sum_{t=1}^{6} \underset{\sim}{PEC}_{k,t}^{\pm}\times EGA_{k,t}^{\pm}\times FE_{k,t}^{\pm}+\sum_{t=1}^{6} \underset{\sim}{PEJ}_{t}^{\pm}\times PE_{t}^{\pm}}_{\text{Cost for importing energy resources and electricity}} + \underbrace{\sum_{k=1}^{6}\sum_{t=1}^{6} EGA_{k,t}^{\pm}\times \underset{\sim}{CU}_{k,t}^{\pm}}_{\text{Cost for electricity transmission}} \\
& + \underbrace{\sum_{k=1}^{6}\sum_{t=1}^{6}\left(EGA_{k,t}^{\pm}\times \underset{\sim}{VGC}_{k,t}^{\pm}\right)+\sum_{k=1}^{6} \underset{\sim}{FGC}_{k,t}^{\pm}\times\left(RC_{k,t=0}^{\pm}+\sum_{t=1}^{6} EC_{k,t}^{\pm}\right)}_{\text{Cost for electricity generation}} + \underbrace{\sum_{k=1}^{6}\sum_{t=1}^{6}\left(\underset{\sim}{FEC}_{k,t}^{\pm}\times YC_{k,t}^{\pm}+\underset{\sim}{VEC}_{k,t}^{\pm}\times EC_{k,t}^{\pm}\right)}_{\text{Cost for capacity expansion}} \\
& + \underbrace{\sum_{k=1}^{6}\sum_{t=1}^{6}\sum_{q=1}^{3} EGA_{k,t}^{\pm}\times\left(3.6\times \underset{\sim}{CP}_{t,q}^{\pm}+\underset{\sim}{CE}_{t,q}^{\pm}/ST_{k,t}^{\pm}-3.6\times \underset{\sim}{SU}_{t}^{\pm}\right)}_{\text{Cost for pollutant reduction}} + \underbrace{\sum_{k=1}^{6}\sum_{t=1}^{6} EGA_{k,t}^{\pm}\times \underset{\sim}{\delta}_{k,t}^{\pm}\times \mu_{k,t}^{\pm}}_{\text{Cost for } CO_2 \text{ mitigation}}
\end{aligned} \tag{4}
$$

The constraints are:

(1) *System joint-risk constraint between water resources availability and electricity demand, which is used for guaranteeing that each individual chance constraint should be satisfied the acceptable joint-risk of constraint violation.*

$$C\left(1-p_1, 1-p_2\right)=1-p \tag{5}$$

(2) *Water resource availability constraint, which is established to ensure that the amount of water consumption must be not less than the total available water resources amounts.*

$$\Pr\left\{\sum_{k=1}^{2} EGA_{k,t}^{\pm}\times\left(CW_{k,t}^{\pm}+BW_{k,t}^{\pm}+DW_{k,t}^{\pm}\right)+\sum_{k=3}^{6} EGA_{k,t}^{\pm}\times OW_{k,t}^{\pm}\leq TAW_{t}^{\pm}\right\}\geq 1-p_1 \tag{6}$$

(3) *Constraint for water demand-supply, which is formulated to ensure that the total water*

consumption (i.e. cooling water, boiler water, desulfurization water and other water) should not be less than the amount of water resources demands.

$$\sum_{k=1}^{2} EGA_{k,t}^{\pm} \times \left(CW_{k,t}^{\pm} + BW_{k,t}^{\pm} + DW_{k,t}^{\pm} \right) + \sum_{k=3}^{6} EGA_{k,t}^{\pm} \times OW_{k,t}^{\pm} \geq WDB_{t}^{\pm} \tag{7}$$

(4) *Energy resource availability constraint: This constraint is established to ensure that the amount of energy utilization must be not less than the total available energy amounts.*

$$EGA_{k,t}^{\pm} \times FE_{k,t}^{\pm} \leq AR_{k,t}^{\pm} \tag{8}$$

(5) *Capacity limitation constraints: These constraints are established to ensure that the capacity will satisfy the demand of electricity from a long-term planning point of view. The related optimization analysis will require the use of integer variables to indicate whether a particular facility development or expansion option needs to be undertaken.*

$$EGA_{k,t}^{\pm} \leq \left(RC_{k,t=0}^{\pm} + \sum_{t'=0}^{t-1} EC_{k,t}^{\pm} \right) \times ST_{k,t}^{\pm} \tag{9a}$$

$$YC_{k,t}^{\pm} \begin{cases} = 1; & \text{if capacity expasion is undertaken} \\ = 0; & \text{if otherwise} \end{cases} \tag{9b}$$

$$0 \leq EC_{k,t}^{\pm} \leq MC_{k,t}^{\pm} \times YC_{k,t}^{\pm} \tag{9c}$$

(6) *Constraint for electricity demand-supply: These constraints are established to ensure that the total electricity generated from the existing and future expanding capacities, and purchased from other power grids should not be less than the amount of electricity demands.*

$$\Pr\left\{ \left(\sum_{k=1}^{6} EGA_{k,t}^{\pm} \times \left(1 - ZL_{k,t}^{\pm}\right) \times TE_{k,t}^{\pm} + PE_{t}^{\pm} \right) \times \left(1 - \eta_{t}^{\pm}\right) \geq EDB_{t}^{\pm} \right\} \geq 1 - p_{2} \tag{10}$$

(7) *Constraint for pollutant and CO_2 emissions: These constraints are used for ensuring that the pollutant-emission amounts should be satisfied by the pollutant-emission permits.*

$$\sum_{k=1}^{6} EGA_{k,t}^{\pm} \times AMR_{k,t,q}^{\pm} \leq ES_{t,q}^{\pm} \tag{11a}$$

$$\sum_{k=1}^{6} EGA_{k,t}^{\pm} \times \delta_{k,t}^{\pm} \times \left(1 - CCA_{t}^{\pm}\right) \leq ESC_{t}^{\pm} \tag{11b}$$

(8) *Nonnegative constraints: This constraint assures that only positive electricity-conversion activities are considered in the solution, eliminating infeasibilities while calculating the solution.*

$$EGA_{k,t}^{\pm},\ PE_{t}^{\pm},\ EC_{k,t}^{\pm} \geq 0 \tag{12}$$

The abbreviation and detailed explanations of system coefficients are given in Appendix. The system coefficients from sociometric, technical, subjective and observed or estimated aspects were collected from the Statistical Yearbook of Henan Province, survey questionnaires and expert consultations, as well as the Henan Provincial Water Resources Bulletin [36-38]. Besides, four classes of copulas such as Clayton, Frank, Gumbel and Student's t copulas were used to model the joint distribution of water resource availability and electricity consumption. The joint cumulative distribution functions for water resources availability and electricity consumption under four copulas were shown in Figure 3. The RMSE, MSE, AIC and BIC values for joint cumulative distributions of these selected copulas were shown in Table 1. Results indicate that Frank copula was superior to other copulas in connecting the marginal distributions of water resource availability and electricity consumption. The selected scenarios for joint and individual constraint-violation levels (p, p_1, p_2), being $(0.1,\ 0.02,\ 0.2)$, $(0.1,\ 0.1,\ 0.3188)$, $(0.1,\ 0.1063,\ 0.1063)$, $(0.1,\ 0.15,\ 0.1001)$ and $(0.1,\ 0.02,\ 0.2)$ from scenario 1 to scenario 5 (abbreviated as S1, S2, S3, S4 and S5), as detailed in [39].

Place Figure 3, Table 1 here

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4. Result Analysis

Figure 4 presents the electricity-supply schemes under different scenarios. Summarily, the percentage of electricity by coal-fired power would change with the variation of scenarios, which range from [79.2, 80.8] % (S1) to [81.8, 82.6] % (S5). This is because low water-resources availability would force the managers to select more renewable energy-based electricity owing to the consideration of system reliability, economic development and water consumption; conversely, managers would tend to choose more local fossil energy-based electricity under high water-resources availability. Besides, since the renewable energy-based electricity is subject to the capacity limitation of renewable energy resources, the variation of associated electricity-generation would change very little. Figure 5 presents the electricity-generation pattern for each power plant in each year. Generally, the local electricity supply is primarily depending on the coal-fired power even having a decreasing trend from [84.1, 85.5] % to [74.9, 76.5] % during the planning horizon. Gas-fired power and hydropower would take minor shares for the WEN system while having an increasing tendency. The remaining power plants such as wind power, solar power and biomass power would occupy small contributions for the local electricity-supply because of the limited energy resources, small capacities, and high investment costs.

Place Figures 4 and 5 here

Figure 6 shows the expanded capacities of power conversion facilities in each year. Summarily, the expanded capacity of each power conversion facility in each year would be different. Coal-fired power would have no expansion scheme while wind power and solar power would have high expansion scheme over the planning horizon. For example, the lower bound of expanded capacity for wind power would be 0.68 GW in year 1, 0.68 GW in year 2, 0.69 GW in year 3, 0.60 GW in year 4, 0.59 GW in year 5 and 0.59 GW in year 6, respectively. This is mainly because decision makers would incline to choose more local electricity-generation having low water-consumption and pollutant-discharge. Moreover, energy management decision makers would prefer to developing local renewable energies in order to improve the local power security and promote urban sustainable development in the long run. Figure 7 depicts the imported electricity under different scenarios. Results disclose that the imported electricity would decrease with time, and the imported electricity would decrease from [176.37, 192.66] $\times10^3$ GWh in year 1 to [175.21, 159.70] $\times10^3$ GWh in year 6 under S1. Results also demonstrate that different scenarios would contribute to varied amounts of imported electricity. The variation of imported electricity would change around 16.3% between S1 and S2 at the end planning horizon.

Place Figures 6 and 7 here

Figure 8 presents the water consumption for each power plant under different scenarios. Generally, interactions of water availability and electricity demand would change the total water consumption, and the total water consumption would approximately increase by [194.9, 203.4] $\times 10^6$ m^3 from S1 to S5. Results also show that coal-fired power consumes more than 90% of the water consumption, and the water consumption of coal-fired power would decrease with time owing to the water availability scenarios (e.g., the more available water resources, the higher coal-fired based electricity).Thus, it is of indispensability to exploit more renewable energies having lower water-requirement to balance contradictions of water demand-supply, electricity demand-supply and pollutant mitigation.

Place Figure 8 here

Figure 9 shows the emissions of three air-pollutants (i.e. SO_2, NO_x and PM_{10}) and CO_2. Results indicate that different water availability scenarios would affect the electricity-generation pattern and then lead to the variation of pollutant-emission pathway (e.g., the emissions of pollutants would have a downward trend from S5 to S1). Moreover, under S5 (i.e. the water resources availability generates none effects on the coal-fired power), the average amount of CO_2 would decrease from 21.63×10^6 tonne (year 1) to 21.30×10^6 tonne (year 6). This is mainly attributed to the fact that many efforts such as strict mitigation target, policy stimulation for renewable energy and improvement of pollutant-mitigation efficiency play jointly contributions for reducing pollutants and CO_2 emissions. Thus, some new technologies (e.g., wind power and solar power) that can both meet electricity-demand and reduce pollutant emissions should be further adopted.

Place Figure 9 here

Uncertainties existed in modeling parameters would lead to varied system costs. As shown in Figure 10, when $\lambda = 1$, system cost would increase by \$ [0.18, 0.19] $\times 10^{12}$ under S1 compared to that under S2, while [194.9, 203.4] $\times 10^6$ m^3 of water were saved. It is mainly because a high water-resources availability violation-risk equivalent to an increased coal-fired power generation reliability, leading to a low system cost; while renewable-energy based and extra electricity from other power grids become of indispensability in response to a low water-resources availability violation-risk, thus resulting in a high system cost. Moreover, different λ levels correspond to decision makers' different necessity degrees of the system cost, thus leading to changed system costs. For instance, the system cost would vary from \$ [2.99, 3.39] × 10^{12} (λ = 1) to \$ [3.02, 3.42] × 10^{12} (λ = 0.65) under S1. Thus, there exists a trade-off among system cost, risk-averse attitude of decision-maker and water resources availability.

Place Figure 10 here

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5. Conclusions

In this study, a CFIP method has been exploited through integration of CRP, IPP and FPP. CFIP can both handle random, interval and interval information and reflect system joint-risk employed to the WEN system of Henan Province, China. Solutions of various copulas associated with different scenarios and necessity degrees are examined in the CFIP-WEN model. CFIP-WEN model has advantages of: (a) disclosing interactions between water resources availability and electricity consumption, and further illustrating their interactive effects on WEN system in association with various scenarios and multiple uncertainties; (b) balancing the conflict among economic objective, water resources shortage and electricity demand, as well as environmental requirement.

Solutions for system cost, electricity-supply pattern, water-allocation pattern, and pollutant-emission associated with various scenarios and multiple uncertainties have been achieved. Results indicate that uncertainties and scenarios employed to water resources, electricity demand and other module parameters can generate prominent impacts on the WEN system. Water resources can restrict the local electricity-generation pattern and then lead to the change of system cost, and the system cost would increase by \$ [0.18, 0.19] × 10^{12} under S1 compared to that under S2, while around [194.9, 203.4] ×10^6 m^3 of water to be saved. Compared to high water-availability scenario (S5), the share of electricity generated by the coal-fired power can decrease by [1.8, 2.6] % under low water-availability scenario (S1).

Although CFIP-WEN model has its effectiveness in reflecting the interactions between water resources availability and electricity demand, and providing optimal solutions for WEN management, it neglects the hierarchically conflicting objectives in the WEN system (e.g., the objectives of minimum system cost and minimum water consumption), making the results incapable of presenting the real-world WEN planning issues [40]. Besides, the constraints of the CFIP-WEN model are limited to production-demand relationships, efficiency, storage and operation levels of the electricity-conversion technologies should be further considered in order to improve the robustness of the CFIP-WEN model [41]. In addition, energy- and water-supply security especially for the water-stressed area is an international challenge, some more advanced theory and robust model should be referenced to cope with such increasing energy demand and water shortage [42].

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A copula-based fuzzy interval-random programming approach for planning water-energy nexus system under uncertainty

L. Yu[1*], Y. Xiao[2], S. Jiang[3*], Y.P. Li[4], Y.R. Fan[5], G.H. Huang[6], J. Lv[7], Q.T. Zuo[8], F.Q. Wang[9]

[1*] (Corresponding Author) School of Water Conservancy Engineering, Zhengzhou University, Zhengzhou 450001, China; Zhengzhou Key Laboratory of Water Resource and Environment, Zhengzhou, 450001, China; Henan Key Laboratory of Groundwater Pollution Prevention and Rehabilitation, Zhengzhou, 450001, China; E-mail: yulei2018@zzu.edu.cn

[2] School of Water Conservancy Engineering, Zhengzhou University, Zhengzhou 450001, China; E-mail: xiaoyaocs@163.com

[3*] (Corresponding Author) Department of water resources, China Institute of Water Resources and Hydropower Research, Beijing 100038, China; E-mail: jiangs@iwhr.com

[4] School of Environment, Beijing Normal University, Beijing 100875, China; E-mail: yongping.li@iseis.org

[5] Department of Civil and Environmental Engineering, Brunel University London, Uxbridge, UB8 3PH, United Kingdom; E-mail: yurui.fan@gmail.com

[6] Institute for Energy, Environment and Sustainable Communities, University of Regina, Regina, Sask. S4S 7H9, Canada; E-mail: gordon.huang@uregina.ca

[7] Sino-Canada Energy and Environmental Research Center, North China Electric Power University, Beijing 102206, China; E-mail: 291697439@qq.com

[8] School of Water Conservancy Engineering, Zhengzhou University, Zhengzhou 450001, China; E-mail: zuoqt@zzu.edu.cn

[9] Department of Water Conservancy Engineering, North China University of Water Resources and Electric Power, Zhengzhou 450046, China; E-mail: wangfuqiang@ncwu.edu.cn

Abstract

Water and energy are closely linked and restrict each other, which has become major restraints to urban development associated with constricted water availability, increased electricity demand and limited environmental capacity. In this study, a copula-based fuzzy interval-random programming method is proposed through integration of copula-based random programming, interval-parameter programming and fuzzy possibilistic programming. It can both handle random, interval and fuzzy information and reflect system joint-risk existed in the water-energy nexus system of Henan Province, China. A class of copulas associated with different water resource-availability and electricity-consumption scenarios as well as various uncertainties are examined. Results disclose that: a) uncertainties and scenarios employed to water resources, electricity demand and other module parameters can generate prominent impacts on the future water-energy nexus system; b) the percentage of electricity by coal-fired power can decrease by [1.8, 2.6] % under low water-availability scenario compared to high water-availability scenario. Findings can provide optimal electricity-supply schemes under the conflicts among economic objective, water resources shortage and electricity demand, as well as environmental requirement.

Keywords: copula, interaction, joint risk, uncertainty, water-energy nexus system

1. Introduction

1.1 Importance

Water and energy, the world's two most critical resources, are gaining international attention from both the general public and the academia [1]. Water and energy are closely linked. The supply, transportation and treatment of water resources need to consume a large amount of energy, while the whole process of energy production from mineral exploitation to electricity generation needs to be completed under the action of water cleaning, cooling and conduction [2]. Water and energy are interdependent and restrict each other, which has become major restraints to urban development [3].China, a largest developing country around the world, occupies 21% of the world's energy consumption and holds 6% of the global fresh water sources [4]. The contradictions among water, energy, air pollution and carbon dioxide (CO_2) emissions are increasingly deteriorative. Moreover, the primary energy bases in China are among the most water-stressed area of the country [5]. Such mismatched geographical space further aggravates the challenge between water shortage and energy security. Although several polices such as "3 Red lines" and "Water allocation plan for coal bases" were enacted to reduce water utilization, improve water efficiency and reduce sewage water discharges in the coal sector, particularly for further managing future coal-fired power plants in water-scarce regions [6]. However, in real-world water-energy nexus (WEN) problems, water and energy resources are associated with social, economic, managerial and environmental limitations [7]. Above of which force researchers to propose effective strategies toward the energy system's water utilization in a mutually-beneficial manner between economic development and environmental mitigation.

1.2 Literature review

Previously, numerous studies were focused on quantitatively analyzing WEN system. For example, Al-Ansari et al. [8] adopted a life cycle assessment (LCA) approach to assess the nexus of water-energy-food (WEF) in food production systems. Wang and Chen [9] developed a multi-regional network model for planning the WEN of Beijing-Tianjin-Hebei urban agglomeration. Chhipi-Shrestha et al. [10] used a system dynamic modelling (SDM) to recognize key factors for the urban water system in Penticton. Khan et al. [11] formulated an integrated agent-based modelling ABM-SWAT (soil and water-assessment tool) model for analyzing the water-energy-food-environment (WEFE) nexus system management in transboundary river basins. Summarily, the above studies are mainly focused on dealing with WEN problems when their system components were deterministic. However, some coefficients are not obtained as deterministic due to the inaccuracy of empirical observations and estimations [12]. Thus, it is of indispensability to exploit more robust optimization techiques for planning WEN corresponding to the associated complexities and uncertainties [13].

Recently, lots of efforts were made in WEN for dealing with uncertainties such as integrated energy system modelling (IESM), multi-objective programming (MOP), two-level programming (TLP), system dynamics approach (SDA). For example, Zhang and Vesselinov [14] proposed a bi-level model for handling the tradeoffs in WEN problems. Bieber et al. [15] developed an integrated modelling for the WEF nexus system, where ABM was used for simulating varied resource demands and scenario-based approaches were used for presenting different policies. Li et al. [16] used an incorporated multi-objective programming method to planning the agricultural WEF, where contradictions among water, energy, food and land are handled. Feng et al. [17] used the system dynamics approach for modeling the nexus across water, power and environment in Hehuang Region, China. In general, the above studies mainly focused on handling WEN tradeoffs through using the modeled scenarios among different policies or varied views of decision makers, and overall satisfaction of the two-level decision makers [18]. However, few of them are specialized in analyzing the intricate and complex interactions of the WEN system. For a real-world WEN system, it includes two subsystems (water subsystem and energy subsystem), and each contains multiple layers and components. Every component in each subsystem can result in changed influence on the other subsystem and pose joint shortage risk between water and energy [19]. Copula approach has its effectiveness in reflecting joint-violation risk through modeling multivariate joint distributions [20].

1.3 Contribution

This study aims to propose a copula-based fuzzy interval-random programming (CFIP) approach for multi-uncertainty reflection by combining copula-based random programming (CRP), interval-parameter programming (IPP) and fuzzy possibilistic programming (FPP). Compared to the deterministic quantitatively analysis methods in Al-Ansari et al. [8], Wang and Chen [9], Chhipi-Shrestha et al. [10] and Khan et al. [11], CFIP can handle complexities and uncertainties existing in WEN management problems. In comparison with the inexact optimization methods in Zhang and Vesselinov [14], Bieber et al. [15], Li et al. [16], and Feng et al. [17], CFIP can not only deal with uncertainties presented by the interval and fuzzy information but also tackle the random water resources availability and electricity demand as well as the correlative system joint-risk. Summarily, CFIP combines the superiority of CRP, IPP and FPP into one framework, which can efficaciously: (a) deal with the uncertainties expressed as random variables, interval values and fuzzy sets as well as their combinations (i.e. interval-fuzzy modulus and interval-random variables); (b) reveal the water-shortage risk, electricity-shortage risk as their correlated joint-shortage risk. Then, a CFIP-WEN model is developed and then applied to the WEN system of Henan Province, China. In the CFIP-WEN model, four classes of copulas (i.e. Clayton, Frank, Gumbel and Student's t copulas), five scenarios with different groups of water resources availability and electricity consumption, four λ levels corresponding to decision makers' different necessity degrees of the system cost are considered. Results will help decision makers: (a) identify the desired electricity-supply patterns under the conflicts among economic objective, water resources shortage and electricity demand as well as environmental requirement; (b) analyze interactions between water resources availability and electricity consumption, and disclose their joint risk on WEN system associated with different scenarios.

2. Methodology

CRP has advantages of capturing the dependence of bivariate or multivariate random variables and binding disparate univariate marginal distributions together through constructing their joint distribution based on a copula function [21]. According to Charnes and Cooper [22], Chen et al. [23], Simic and Dabic-Ostojic [24], a generic CRP model can be depicted as

$$\text{Min } E = \sum_{j=1}^{n} c_j x_j \tag{1a}$$

subject to:

$$\sum_{j=1}^{n} a_{ij} x_j \le b_i^{p_i},\ i = 1, 2, ..., k \quad (1b)$$

$$C(1-p_1, 1-p_2, ..., 1-p_k) = 1-p \quad (1c)$$

$$\sum_{j=1}^{n} a_{ij} x_j \le b_i,\ i = k+1, k+2, ..., m \quad (1d)$$

$$x_j \ge 0,\ j = 1, 2, ..., n \quad (1e)$$

where x_j are decision variables; a_{ij} and b_i are coefficients; $b_i^{p_i}$ are random variables; C is the determinate copula; p_i $(i = 1, 2, ..., k)$ are constraint-violation levels; $b_i^{p_i} = F_i^{-1}(p_i)$.

For a real-world WEN system, some economic parameters are affected by the socio-economic, political, legislation and technical factors, which can hard to be achieved as stochastic variables but can be presented as interval values through using the IPP technique [25]. Some imprecise data can rarely be achieved as randomness and interval but can be presented by fuzzy sets [26]. Through introducing IPP and FPP into CRP, a CFIP model can be formulated as:

$$\text{Min } \underset{\sim}{E}^{\pm} = \sum_{j=1}^{n} \underset{\sim}{c}_j^{\pm} x_j^{\pm} \quad (2a)$$

subject to:

$$\sum_{j=1}^{n} a_{ij}^{\pm} x_j^{\pm} \le b_i^{(p_i)\pm},\ i = 1, 2, ..., k \quad (2b)$$

$$C(1-p_1, 1-p_2, ..., 1-p_k) = 1-p \quad (2c)$$

$$\sum_{j=1}^{n} a_{ij}^{\pm} x_j^{\pm} \le b_i^{\pm},\ i = k+1, k+2, ..., m \quad (2d)$$

$$x_j^{\pm} \ge 0,\ j = 1, 2, ..., n \quad (2e)$$

where $a_{ij}^{\pm} \in \{R^{\pm}\}^{m\times n}, b_i^{\pm} \in \{R^{\pm}\}^{m\times 1}, \underset{\sim}{c}_j^{\pm} \in \{R^{\pm}\}^{1\times n}, x_j^{\pm} \in \{R^{\pm}\}^{n\times 1}$; $R^{\pm}$ mean interval numbers; $\underset{\sim}{c}_j^{\pm}$ represent fuzzy-boundary intervals. Based on Inuiguchi and Ramik [27], Model (2) can be converted into:

$$\text{Min } \underset{\sim}{E}^{\pm} = \left(\sum_{j=1}^{k} c_j^{c\pm} x_j^{\pm} + \sum_{j=1}^{k} \lambda \varpi_j \, | x_j^{\pm} | + \sum_{j=k+1}^{n} c_j^{'c\pm} x_j^{\pm} + \sum_{j=k+1}^{n} \lambda \varpi_j^{'} \, | x_j^{\pm} | \right) \tag{3a}$$

subject to:

$$\sum_{j=1}^{l} a_{ij}^{\pm} x_j^{\pm} + \sum_{j=l+1}^{n} a_{ij}^{\pm} x_j^{\pm} \le b_i^{(p_i)\pm}, \; i = 1, 2, ..., k \tag{3b}$$

$$C(1-p_1, 1-p_2, ..., 1-p_k) = 1-p \tag{3c}$$

$$\sum_{j=1}^{l} a_{ij}^{\pm} x_j^{\pm} + \sum_{j=l+1}^{n} a_{ij}^{\pm} x_j^{\pm} \le b_i^{\pm}, \; i = k+1, k+2, ..., m \tag{3d}$$

$$x_j^{\pm} \ge 0, \; j = 1, 2, ..., n \tag{3e}$$

where λ means p-necessity level [28]. In this study, two-step method (TSM) is used for obtaining interval values of the CFIP model (i.e. $f_{\text{opt}}^{\pm} = [f_{\text{opt}}^{-}, f_{\text{opt}}^{+}]$ and $x_{\text{opt}}^{\pm} = [x_{\text{opt}}^{-}, x_{\text{opt}}^{+}]$) under each p level and each λ level [29].

3. Case Study

Henan Province sits in the central China and covers an area of 167 × 10^3 km^2. It consists of 17 prefectural-level cities and 1 city administrated by province, as shown in Figure 1. In 2017, the gross domestic product (GDP) and total population of Henan reached to RMB¥ 4,498.82 billion and 108.53 million, respectively. Most rivers in Henan originate from mountainous areas in the west, northwest and southeast, among which 560 rivers covering an area of more than 100 km^2. The annual average amounts of water resources reached 40.35 billion m^3, ranking 19th in China. However, the per capita water resources were about 383 m^3, merely accounting for one-fifth of the national average. The limited water resources and increased water demand are increasingly restricting the sustainable development of Henan Province accompanied with anticipated climate change [30].

Place Figure 1 here

As a primary agricultural province, agriculture occupies the primary role in the whole water use, followed by the industry, consumption and ecological protection sectors (Figure 2).For Henan Province, several electricity-conversion technologies such as conventional thermal plants (coal-fired power and nature gas-fired power) and renewable-energy based power plants (hydropower, wind, solar and biomass power) are mainly used for satisfying the local electricity demand. Simultaneously, the conversion processes of these facilities also need water in cooling, steam generation, desulfurization and cleaning. In this study, the modeling parameters are presented as interval values, probability distributions, fuzzy sets as well as their correlated dual uncertainties (i.e. interval-fuzzy modulus and interval-random variables). For example, the correlative water-consumption is subjected to a range of factors (i.e. electricity conversion type, cooling mode, as well as other weather conditions) [4]. The pollutant-emission coefficients and other technical parameters (i.e. residual capacity, capacity expansion, service time, energy consumption rate and power consumption rate) are associated with series of factors such as the energy resources type, energy quality, combustion condition and operation condition, as well as other weather conditions [31]. Thus the correlative water-consumption parameters, pollutant-emission coefficients and other technical parameters are expressed as intervals. Economic coefficients which are closely related to the volatility of interest rates, inflation rates and other factors (i.e., energy price, labor fee, and operation condition) are presented as interval-fuzzy modulus with known fuzzy possibility distributions [32]. Water resources availability and electricity demand which are affected by meteorologic, hydrologic and sociometric conditions are presented as interval-random variables [33].

Place Figure 2

Based on the CFIP method, a provincial-scale CFIP-WEN model is formulated for the purpose of minimizing the system cost, which consists of cost of water resources, energy resources, electricity-generation, -import and -transmission as well as contamination controlling. For example, for a real-world WEN system planning issues, the cost of water resources for electricity generation mainly consists of the processes of cooling, boiling and desulfurization as well as others [32]. Energy import cost includes the cost of importing local and adjacent energies during the conversion activities such as the purchase price of energy resources, workers' wage, truck rental fees and the cost for energy transport losses [34]. The electricity-generation cost always covers a wide range which including unit start-up cost, workers' wage, equipment-maintenance cost and taxation expense. The investment for expanding electricity-conversion technologies such as finance investment, labor fee, equipment maintenance and operation cost, as well as taxation expense [31]. And the pollutant and CO_2 treatment costs can be calculated in terms of the associated emission rates and the unit cost of environmental facilities under various process activities [35]. Therefore, the objective function is:

$$
\begin{aligned}
\text{Min } \utilde{E}^{\pm} = & \overbrace{\sum_{k=1}^{2}\sum_{t=1}^{6} EGA_{k,t}^{\pm} \times \left(\utilde{CCW}_{k,t}^{\pm} \times CW_{k,t}^{\pm} + \utilde{CBW}_{k,t}^{\pm} \times BW_{k,t}^{\pm} + \utilde{CDW}_{k,t}^{\pm} \times DW_{k,t}^{\pm} \right) + \sum_{k=3}^{6}\sum_{t=1}^{6} EGA_{k,t}^{\pm} \times \utilde{COW}_{k,t}^{\pm} \times OW_{k,t}^{\pm}}^{\textit{Cost of water resource for electricity generation}} \\
& + \underbrace{\sum_{k=1}^{2}\sum_{t=1}^{6} \utilde{PEC}_{k,t}^{\pm} \times EGA_{k,t}^{\pm} \times FE_{k,t}^{\pm} + \sum_{t=1}^{6} \utilde{PEJ}_{t}^{\pm} \times PE_{t}^{\pm}}_{\textit{Cost for importing energy resources and electricity}} + \underbrace{\sum_{k=1}^{6}\sum_{t=1}^{6} EGA_{k,t}^{\pm} \times \utilde{CU}_{k,t}^{\pm}}_{\textit{Cost for electricity transmission}} \\
& + \underbrace{\sum_{k=1}^{6}\sum_{t=1}^{6} \left(EGA_{k,t}^{\pm} \times \utilde{VGC}_{k,t}^{\pm} \right) + \sum_{k=1}^{6} \utilde{FGC}_{k,t}^{\pm} \times \left(RC_{k,t=0}^{\pm} + \sum_{t=1}^{6} EC_{k,t}^{\pm} \right)}_{\textit{Cost for electricity generation}} + \underbrace{\sum_{k=1}^{6}\sum_{t=1}^{6} \left(\utilde{FEC}_{k,t}^{\pm} \times YC_{k,t}^{\pm} + \utilde{VEC}_{k,t}^{\pm} \times EC_{k,t}^{\pm} \right)}_{\textit{Cost for capacity expansion}} \\
& + \underbrace{\sum_{k=1}^{6}\sum_{t=1}^{6}\sum_{q=1}^{3} EGA_{k,t}^{\pm} \times \left(3.6 \times \utilde{CP}_{t,q}^{\pm} + \utilde{CE}_{t,q}^{\pm} / ST_{k,t}^{\pm} - 3.6 \times \utilde{SU}_{t}^{\pm} \right)}_{\textit{Cost for pollutant reduction}} + \underbrace{\sum_{k=1}^{6}\sum_{t=1}^{6} EGA_{k,t}^{\pm} \times \utilde{\delta}_{k,t}^{\pm} \times \mu_{k,t}^{\pm}}_{\textit{Cost for } CO_2 \textit{ mitigation}}
\end{aligned} \tag{4}
$$

The constraints are:

(1) *System joint-risk constraint between water resources availability and electricity demand, which is used for guaranteeing that each individual chance constraint should be satisfied the acceptable joint-risk of constraint violation.*

$$C\left(1-p_1, 1-p_2\right) = 1-p \tag{5}$$

(2) *Water resource availability constraint, which is established to ensure that the amount of water consumption must be not less than the total available water resources amounts.*

$$\Pr\left\{ \sum_{k=1}^{2} EGA_{k,t}^{\pm} \times \left(CW_{k,t}^{\pm} + BW_{k,t}^{\pm} + DW_{k,t}^{\pm} \right) + \sum_{k=3}^{6} EGA_{k,t}^{\pm} \times OW_{k,t}^{\pm} \le TAW_{t}^{\pm} \right\} \ge 1 - p_1 \tag{6}$$

(3) *Constraint for water demand-supply, which is formulated to ensure that the total water*

consumption (i.e. cooling water, boiler water, desulfurization water and other water) should not be less than the amount of water resources demands.

$$\sum_{k=1}^{2} EGA_{k,t}^{\pm} \times \left(CW_{k,t}^{\pm} + BW_{k,t}^{\pm} + DW_{k,t}^{\pm} \right) + \sum_{k=3}^{6} EGA_{k,t}^{\pm} \times OW_{k,t}^{\pm} \geq WDB_{t}^{\pm} \tag{7}$$

(4) *Energy resource availability constraint: This constraint is established to ensure that the amount of energy utilization must be not less than the total available energy amounts.*

$$EGA_{k,t}^{\pm} \times FE_{k,t}^{\pm} \leq AR_{k,t}^{\pm} \tag{8}$$

(5) *Capacity limitation constraints: These constraints are established to ensure that the capacity will satisfy the demand of electricity from a long-term planning point of view. The related optimization analysis will require the use of integer variables to indicate whether a particular facility development or expansion option needs to be undertaken.*

$$EGA_{k,t}^{\pm} \leq \left(RC_{k,t=0}^{\pm} + \sum_{t'=0}^{t-1} EC_{k,t}^{\pm} \right) \times ST_{k,t}^{\pm} \tag{9a}$$

$$YC_{k,t}^{\pm} \begin{cases} = 1; & \text{if capacity expasion is undertaken} \\ = 0; & \text{if otherwise} \end{cases} \tag{9b}$$

$$0 \leq EC_{k,t}^{\pm} \leq MC_{k,t}^{\pm} \times YC_{k,t}^{\pm} \tag{9c}$$

(6) *Constraint for electricity demand-supply: These constraints are established to ensure that the total electricity generated from the existing and future expanding capacities, and purchased from other power grids should not be less than the amount of electricity demands.*

$$\Pr\left\{ \left(\sum_{k=1}^{6} EGA_{k,t}^{\pm} \times \left(1 - ZL_{k,t}^{\pm}\right) \times TE_{k,t}^{\pm} + PE_{t}^{\pm} \right) \times \left(1 - \eta_{t}^{\pm}\right) \geq EDB_{t}^{\pm} \right\} \geq 1 - p_2 \tag{10}$$

(7) *Constraint for pollutant and CO_2 emissions: These constraints are used for ensuring that the pollutant-emission amounts should be satisfied by the pollutant-emission permits.*

$$\sum_{k=1}^{6} EGA_{k,t}^{\pm} \times AMR_{k,t,q}^{\pm} \leq ES_{t,q}^{\pm} \tag{11a}$$

$$\sum_{k=1}^{6} EGA_{k,t}^{\pm} \times \delta_{k,t}^{\pm} \times \left(1 - CCA_{t}^{\pm}\right) \leq ESC_{t}^{\pm} \tag{11b}$$

(8) *Nonnegative constraints: This constraint assures that only positive electricity-conversion activities are considered in the solution, eliminating infeasibilities while calculating the solution.*

$$EGA_{k,t}^{\pm},\ PE_{t}^{\pm},\ EC_{k,t}^{\pm} \geq 0 \tag{12}$$

The abbreviation and detailed explanations of system coefficients are given in Appendix. The system coefficients from sociometric, technical, subjective and observed or estimated aspects were collected from the Statistical Yearbook of Henan Province, survey questionnaires and expert consultations, as well as the Henan Provincial Water Resources Bulletin [36-38]. Besides, four classes of copulas such as Clayton, Frank, Gumbel and Student's t copulas were used to model the joint distribution of water resource availability and electricity consumption. The joint cumulative distribution functions for water resources availability and electricity consumption under four copulas were shown in Figure 3. The RMSE, MSE, AIC and BIC values for joint cumulative distributions of these selected copulas were shown in Table 1. Results indicate that Frank copula was superior to other copulas in connecting the marginal distributions of water resource availability and electricity consumption. The selected scenarios for joint and individual constraint-violation levels $\left(p, p_1, p_2\right)$, being $\left(0.1,\ 0.02,\ 0.2\right)$, $\left(0.1,\ 0.1,\ 0.3188\right)$, $\left(0.1,\ 0.1063,\ 0.1063\right)$, $\left(0.1,\ 0.15,\ 0.1001\right)$ and $\left(0.1,\ 0.02,\ 0.2\right)$ from scenario 1 to scenario 5 (abbreviated as S1, S2, S3, S4 and S5), as detailed in [39].

Place Figure 3, Table 1 here

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4. Result Analysis

Figure 4 presents the electricity-supply schemes under different scenarios. Summarily, the percentage of electricity by coal-fired power would change with the variation of scenarios, which range from [79.2, 80.8] % (S1) to [81.8, 82.6] % (S5). This is because low water-resources availability would force the managers to select more renewable energy-based electricity owing to the consideration of system reliability, economic development and water consumption; conversely, managers would tend to choose more local fossil energy-based electricity under high water-resources availability. Besides, since the renewable energy-based electricity is subject to the capacity limitation of renewable energy resources, the variation of associated electricity-generation would change very little. Figure 5 presents the electricity-generation pattern for each power plant in each year. Generally, the local electricity supply is primarily depending on the coal-fired power even having a decreasing trend from [84.1, 85.5] % to [74.9, 76.5] % during the planning horizon. Gas-fired power and hydropower would take minor shares for the WEN system while having an increasing tendency. The remaining power plants such as wind power, solar power and biomass power would occupy small contributions for the local electricity-supply because of the limited energy resources, small capacities, and high investment costs.

Place Figures 4 and 5 here

Figure 6 shows the expanded capacities of power conversion facilities in each year. Summarily, the expanded capacity of each power conversion facility in each year would be different. Coal-fired power would have no expansion scheme while wind power and solar power would have high expansion scheme over the planning horizon. For example, the lower bound of expanded capacity for wind power would be 0.68 GW in year 1, 0.68 GW in year 2, 0.69 GW in year 3, 0.60 GW in year 4, 0.59 GW in year 5 and 0.59 GW in year 6, respectively. This is mainly because decision makers would incline to choose more local electricity-generation having low water-consumption and pollutant-discharge. Moreover, energy management decision makers would prefer to developing local renewable energies in order to improve the local power security and promote urban sustainable development in the long run. Figure 7 depicts the imported electricity under different scenarios. Results disclose that the imported electricity would decrease with time, and the imported electricity would decrease from [176.37, 192.66] $\times 10^3$ GWh in year 1 to [175.21, 159.70] $\times 10^3$ GWh in year 6 under S1. Results also demonstrate that different scenarios would contribute to varied amounts of imported electricity. The variation of imported electricity would change around 16.3% between S1 and S2 at the end planning horizon.

Place Figures 6 and 7 here

Figure 8 presents the water consumption for each power plant under different scenarios. Generally, interactions of water availability and electricity demand would change the total water consumption, and the total water consumption would approximately increase by [194.9, 203.4] $\times 10^6$ m^3 from S1 to S5. Results also show that coal-fired power consumes more than 90% of the water consumption, and the water consumption of coal-fired power would decrease with time owing to the water availability scenarios (e.g., the more available water resources, the higher coal-fired based electricity).Thus, it is of indispensability to exploit more renewable energies having lower water-requirement to balance contradictions of water demand-supply, electricity demand-supply and pollutant mitigation.

Place Figure 8 here

Figure 9 shows the emissions of three air-pollutants (i.e. SO_2, NO_x and PM_{10}) and CO_2. Results indicate that different water availability scenarios would affect the electricity-generation pattern and then lead to the variation of pollutant-emission pathway (e.g., the emissions of pollutants would have a downward trend from S5 to S1). Moreover, under S5 (i.e. the water resources availability generates none effects on the coal-fired power), the average amount of CO_2 would decrease from 21.63×10^6 tonne (year 1) to 21.30×10^6 tonne (year 6). This is mainly attributed to the fact that many efforts such as strict mitigation target, policy stimulation for renewable energy and improvement of pollutant-mitigation efficiency play jointly contributions for reducing pollutants and CO_2 emissions. Thus, some new technologies (e.g., wind power and solar power) that can both meet electricity-demand and reduce pollutant emissions should be further adopted.

Place Figure 9 here

Uncertainties existed in modeling parameters would lead to varied system costs. As shown in Figure 10, when $\lambda = 1$, system cost would increase by \$ [0.18, 0.19] $\times 10^{12}$ under S1 compared to that under S2, while [194.9, 203.4] $\times 10^6$ m^3 of water were saved. It is mainly because a high water-resources availability violation-risk equivalent to an increased coal-fired power generation reliability, leading to a low system cost; while renewable-energy based and extra electricity from other power grids become of indispensability in response to a low water-resources availability violation-risk, thus resulting in a high system cost. Moreover, different λ levels correspond to decision makers' different necessity degrees of the system cost, thus leading to changed system costs. For instance, the system cost would vary from \$ [2.99, 3.39] × 10^{12} (λ = 1) to \$ [3.02, 3.42] × 10^{12} (λ = 0.65) under S1. Thus, there exists a trade-off among system cost, risk-averse attitude of decision-maker and water resources availability.

Place Figure 10 here

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5. Conclusions

In this study, a CFIP method has been exploited through integration of CRP, IPP and FPP. CFIP can both handle random, interval and interval information and reflect system joint-risk employed to the WEN system of Henan Province, China. Solutions of various copulas associated with different scenarios and necessity degrees are examined in the CFIP-WEN model. CFIP-WEN model has advantages of: (a) disclosing interactions between water resources availability and electricity consumption, and further illustrating their interactive effects on WEN system in association with various scenarios and multiple uncertainties; (b) balancing the conflict among economic objective, water resources shortage and electricity demand, as well as environmental requirement.

Solutions for system cost, electricity-supply pattern, water-allocation pattern, and pollutant-emission associated with various scenarios and multiple uncertainties have been achieved. Results indicate that uncertainties and scenarios employed to water resources, electricity demand and other module parameters can generate prominent impacts on the WEN system. Water resources can restrict the local electricity-generation pattern and then lead to the change of system cost, and the system cost would increase by \$ [0.18, 0.19] × 10^{12} under S1 compared to that under S2, while around [194.9, 203.4] ×10^6 m^3 of water to be saved. Compared to high water-availability scenario (S5), the share of electricity generated by the coal-fired power can decrease by [1.8, 2.6] % under low water-availability scenario (S1).

Although CFIP-WEN model has its effectiveness in reflecting the interactions between water resources availability and electricity demand, and providing optimal solutions for WEN management, it neglects the hierarchically conflicting objectives in the WEN system (e.g., the objectives of minimum system cost and minimum water consumption), making the results incapable of presenting the real-world WEN planning issues [40]. Besides, the constraints of the CFIP-WEN model are limited to production-demand relationships, efficiency, storage and operation levels of the electricity-conversion technologies should be further considered in order to improve the robustness of the CFIP-WEN model [41]. In addition, energy- and water-supply security especially for the water-stressed area is an international challenge, some more advanced theory and robust model should be referenced to cope with such increasing energy demand and water shortage [42].

Acknowledgements

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Table 1. Comparison of RMSE, MSE, AIC and BIC values for joint distributions using different copulas

Copula family	RMSE	MSE	AIC	BIC
Clayton	0.1517	0.0230	-43.2646	-42.7797
Frank	0.0567	0.0032	-66.8662	-66.3813
Gumbel	0.1517	0.0230	-43.2646	-42.7797
Student's t	0.0624	0.0039	-62.5922	-61.6224

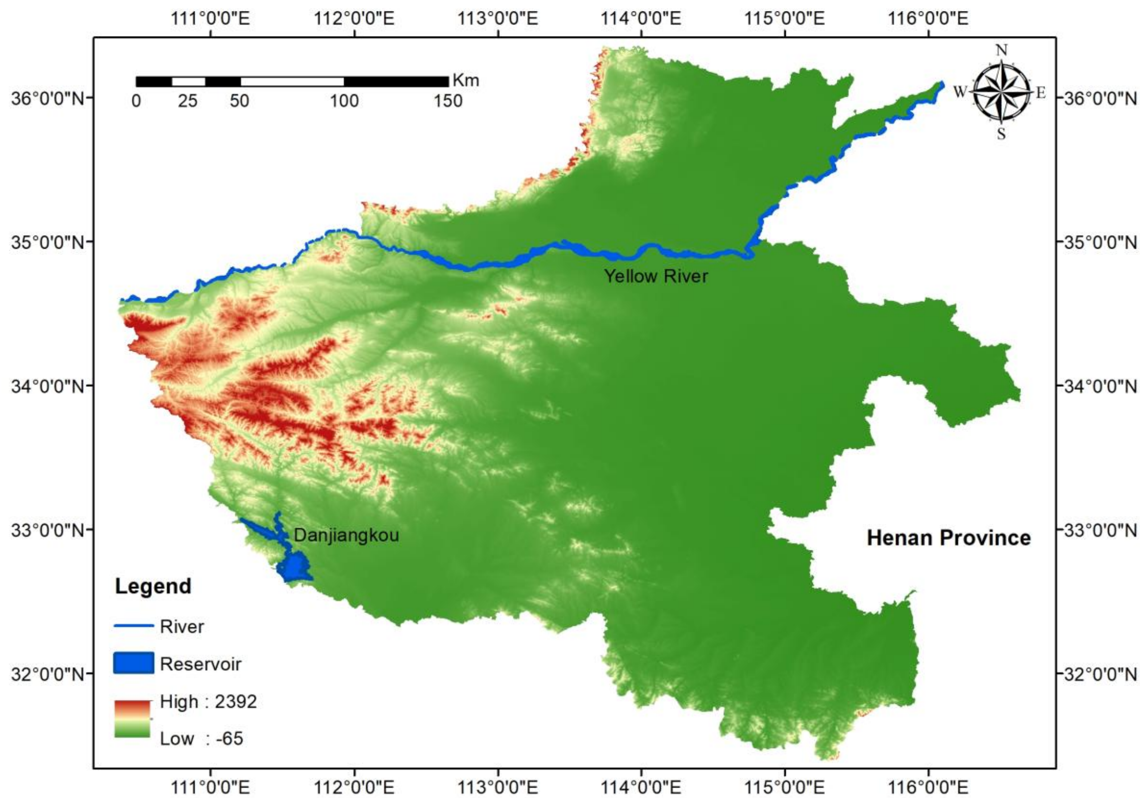

Figure 1. The study area

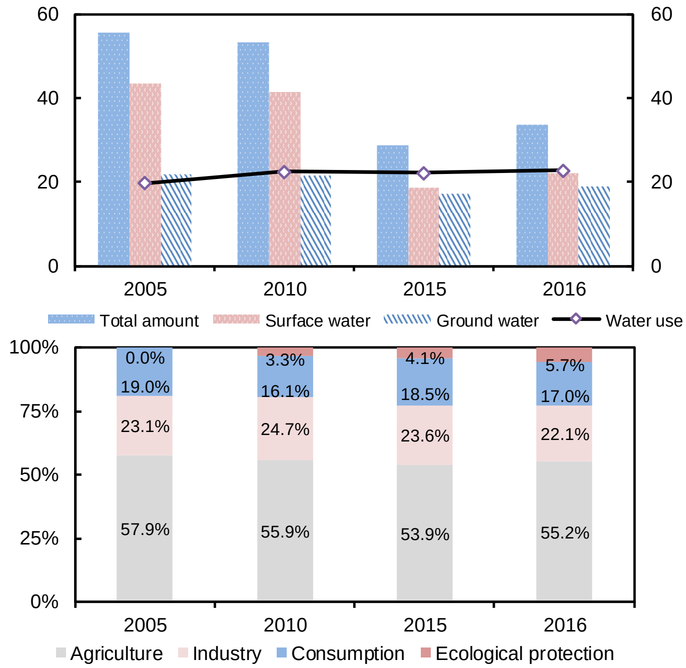

Figure 2. Total water resources and -use under different sectors (10^9 m^3)

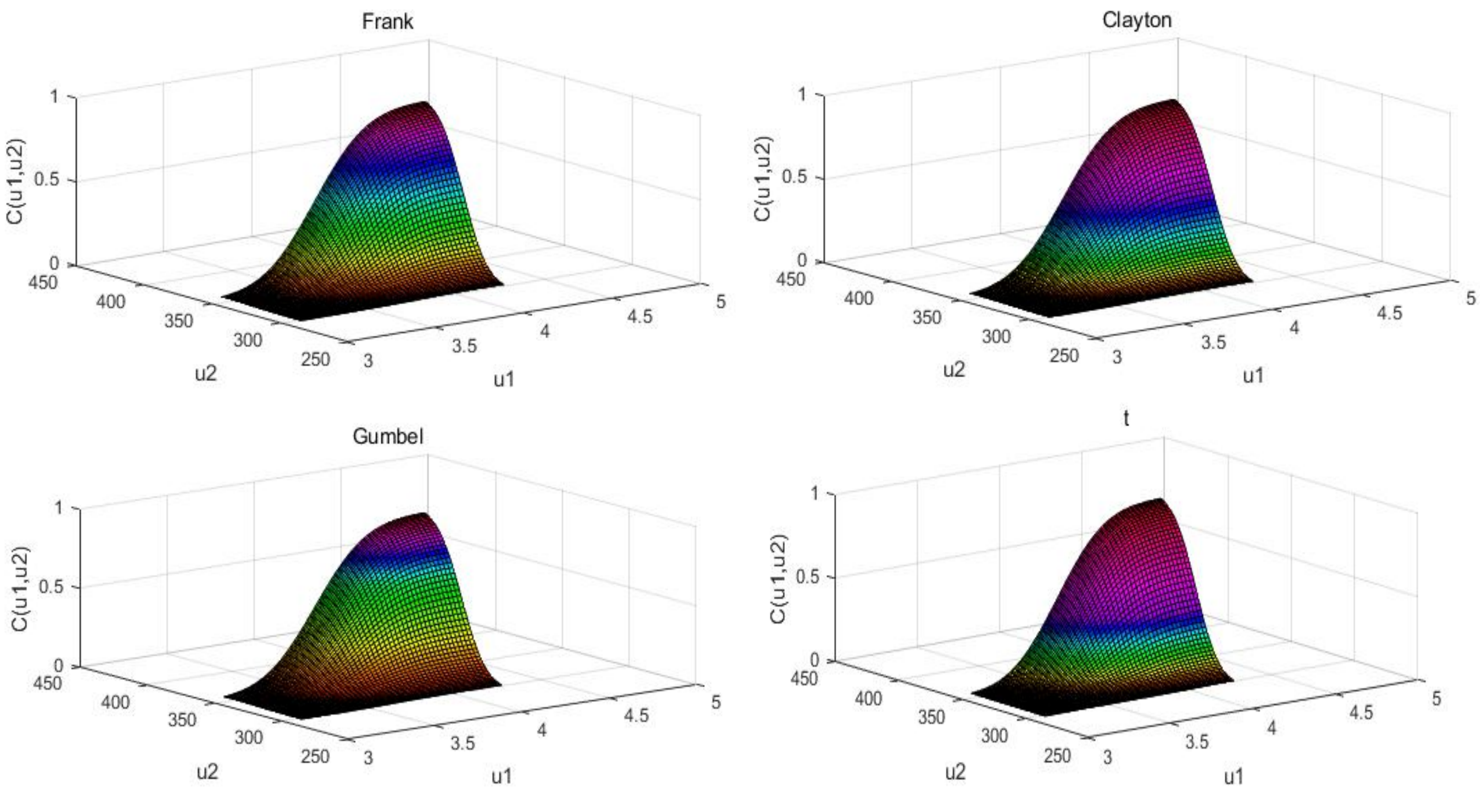

Figure 3. Joint cumulative distribution functions for water resource availability and electricity consumption under different copulas [symbols "u1, u2 and C(u1, u2)" denote "water resource (10^8 m^3), electricity consumption (10^3 GWh) and joint cumulative distribution function", respectively]

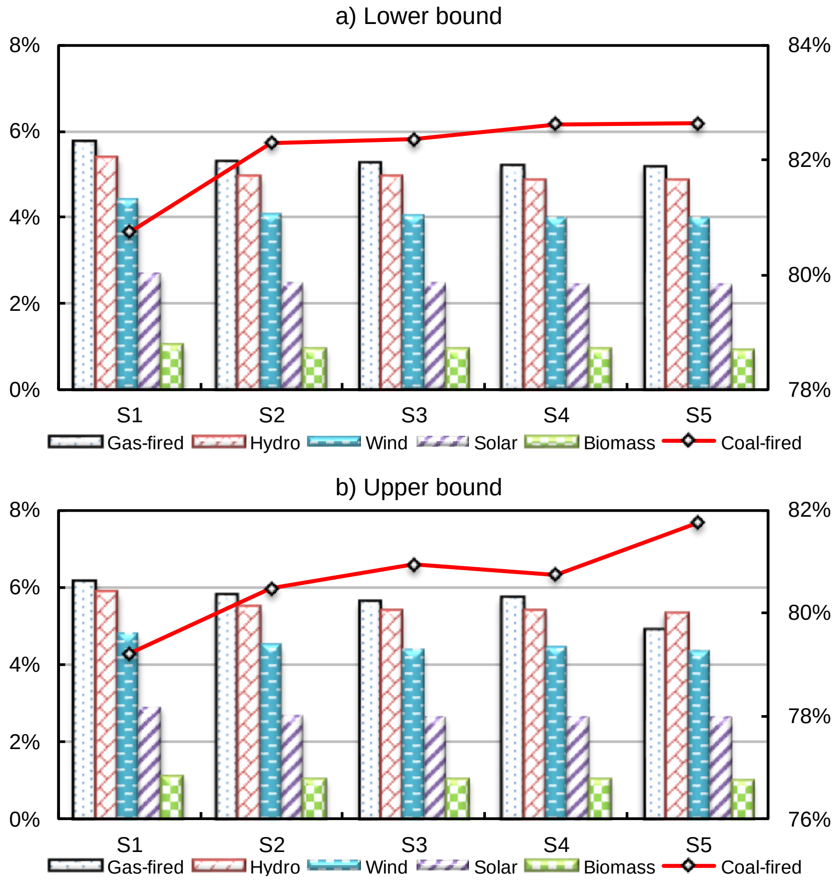

Figure 4. Electricity-supply scheme in the planning horizon (%)

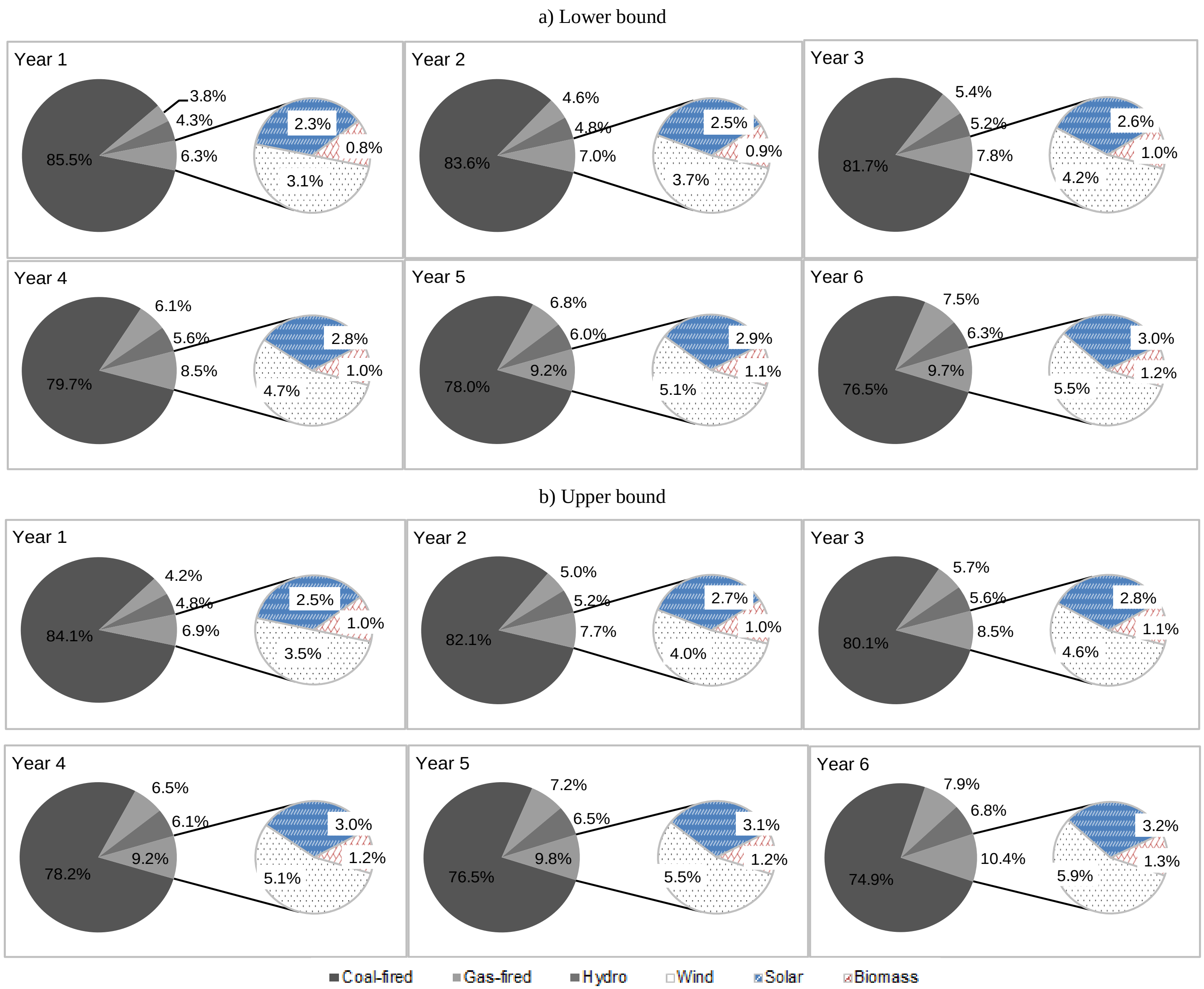

Figure 5. Electricity-supply scheme in each period (%)

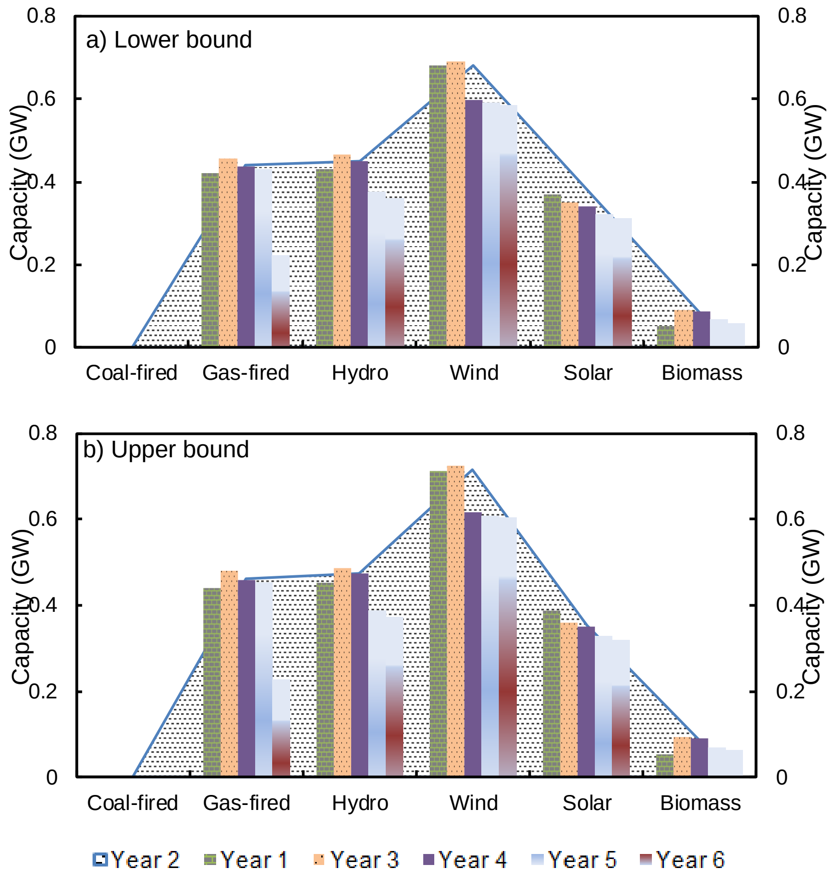

Figure 6. Expanded capacities of power conversion facilities (GW)

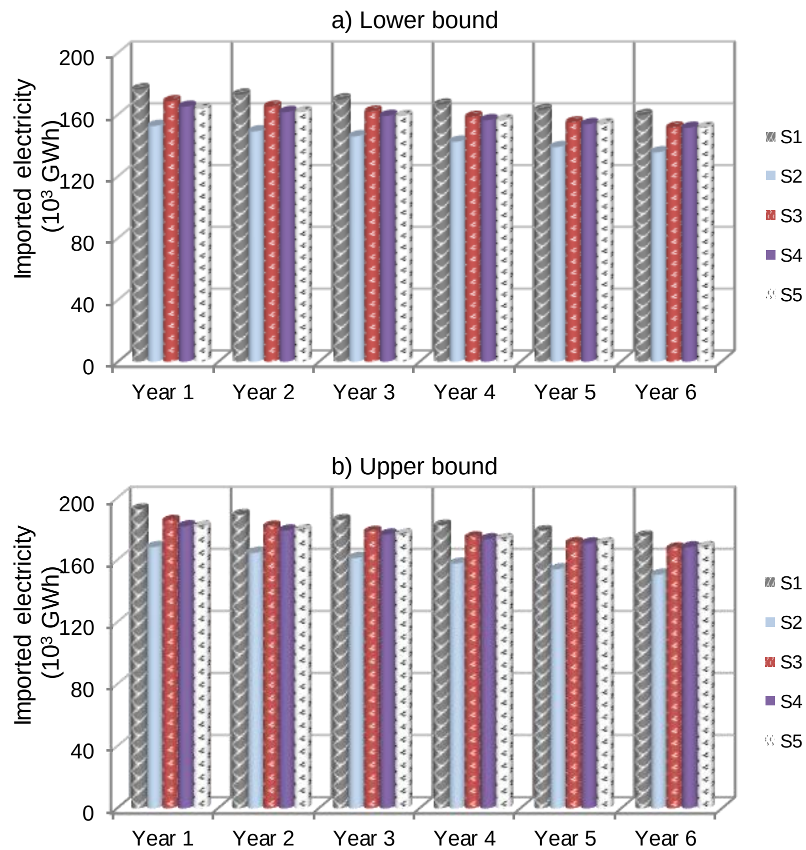

Figure 7. Imported electricity under different scenarios (10^3 GWh)

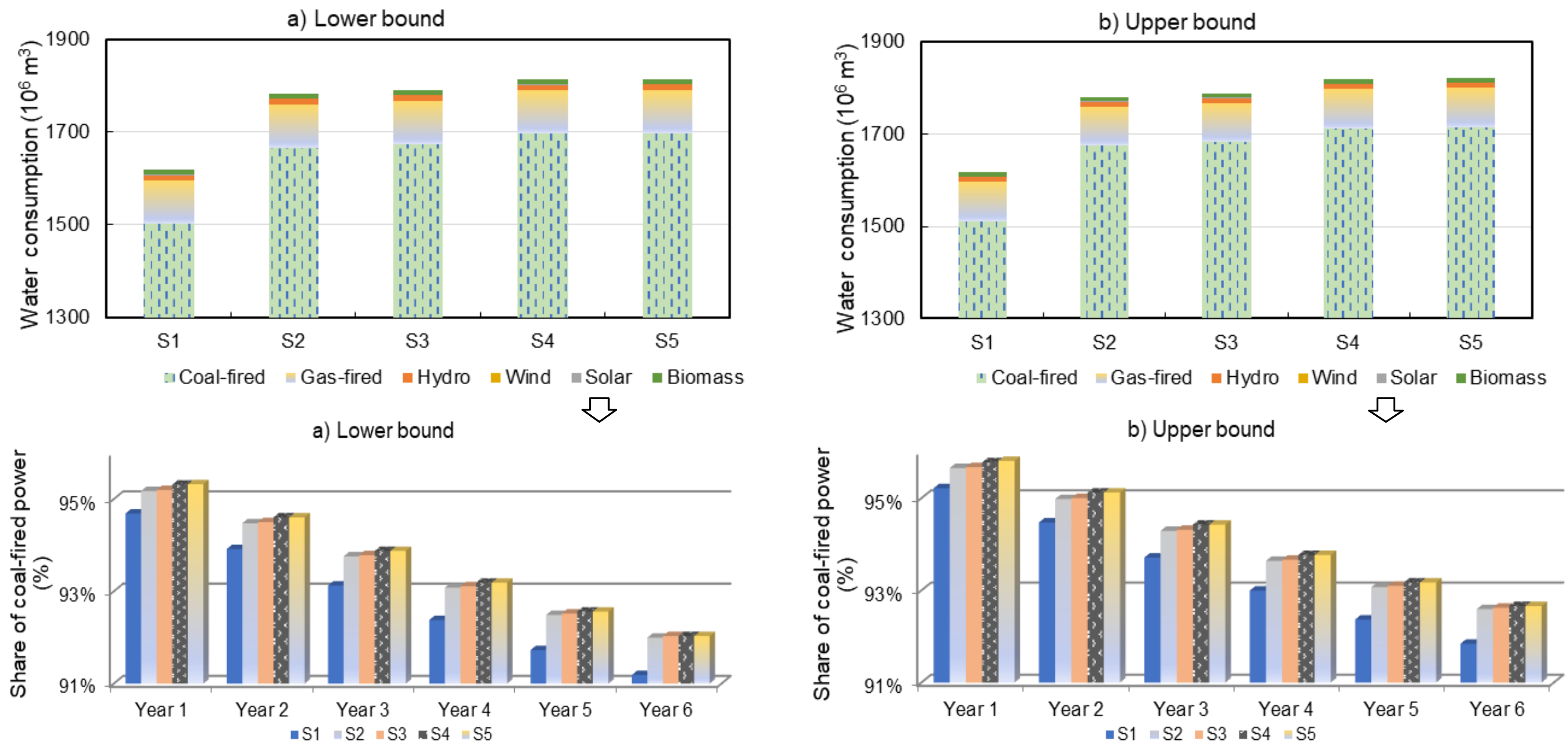

Figure 8. Water consumption (10^6 m^3)

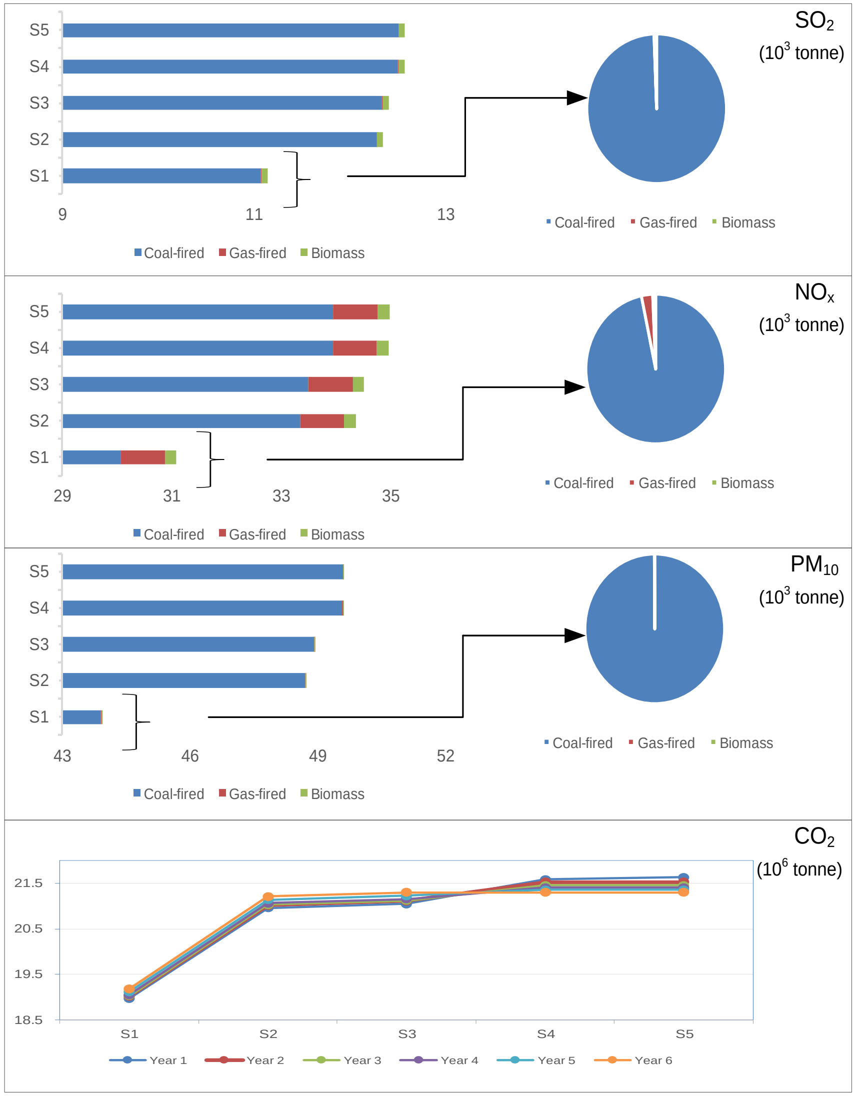

Figure 9. Pollutant and CO_2 emissions

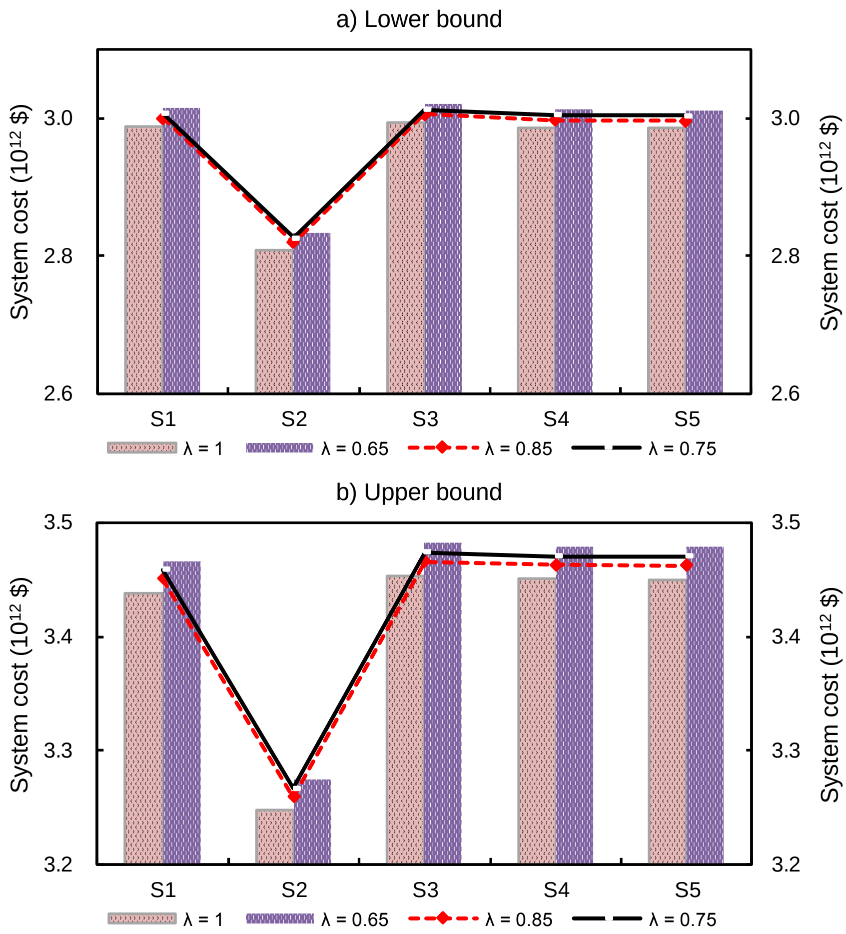

Figure 10. System costs ($ 10^{12})

Abbreviation:

ABM	agent-based modelling
AIC	Akaike information criterion
BIC	Bayesian information criteria
CFIP	copula-based fuzzy interval-random programming
CO_2	carbon dioxide
CRP	copula-based random programming
ENA	ecological network analysis
FPP	fuzzy possibilistic programming
GDP	gross domestic product
IESM	integrated energy system modelling
IO	input-output
IPP	interval-parameter programming
LCA	life cycle assessment
MOP	multi-objective programming
MSE	mean square error
NO_x	nitrogen oxides
PM_{10}	particulate matter
RMSE	root mean square error
SDM	system dynamic modelling
SO_2	sulfur dioxide
WEFE	water-energy-food-environment
WEN	water-energy nexus

Explanations for system coefficients:

$\underset{\sim}{E}^{\pm}$	system cost (\$ 10^{12})
k	electricity-conversion technology, including coal, gas, hydro, wind, solar and biomass power
q	pollutant type, including SO_2, NO_x and PM_{10}
t	time periods (1-6)
$\underset{\sim}{\delta}_{k,t}^{\pm}$	CO_2-emission coefficient (tonne/GWh)
$\eta_t^{\pm}$	transmission loss (%)
$AMR_{k,t,q}^{\pm}$	pollutant-emission coefficients (tonne/GWh)
$AR_{k,t}^{\pm}$	available energy resources (TJ)
$BW_{k,t}^{\pm}$	boiler water for electricity-conversion technology (10^6 m^3/TJ)
$\underset{\sim}{CE}_{t,q}^{\pm}$	cost for pollutant emission (10^3 \$/GW)
$\underset{\sim}{CP}_{t,q}^{\pm}$	cost for pollutant control (10^3 \$/GWh)
$\underset{\sim}{CU}_{k,t}^{\pm}$	cost for electricity transmission (10^3 \$/GWh)
$CW_{k,t}^{\pm}$	cooling water for electricity-conversion technology (10^6 m^3/TJ)
$\underset{\sim}{CBW}_{k,t}^{\pm}$	cost for boiler water (10^3 \$/m^3)
$CCA_t^{\pm}$	Carbon complement efficiency (%)
$\underset{\sim}{CCW}_{k,t}^{\pm}$	cost for cooling water (10^3 \$/m^3)
$\underset{\sim}{CDW}_{k,t}^{\pm}$	cost for desulfurization water (10^3 \$/m^3)
$\underset{\sim}{COW}_{k,t}^{\pm}$	cost for other water (10^3 \$/m^3)
$DW_{k,t}^{\pm}$	desulfurization water for electricity-conversion technology (10^6 m^3/TJ)
$EC_{k,t}^{\pm}$	expanded capacity for electricity-conversion technologies (GW)
$EDB_t^{\pm}$	electricity demand (GWh)
$EGA_{k,t}^{\pm}$	electricity-generation amounts (GWh)
$ES_{t,q}^{\pm}$	allowed pollutant discharge amounts (10^3 tonne)
$ESC_t^{\pm}$	allowed CO_2 discharge amount (10^6 tonne)
$FE_{k,t}^{\pm}$	energy consumption rate (TJ/GWh)
$\underset{\sim}{FEC}_{k,t}^{\pm}$	fixed cost for electricity expansion (10^3 \$/GW)
$\underset{\sim}{FGC}_{k,t}^{\pm}$	fixed maintenance cost for generating electricity (10^6 \$/GW)
$MC_{k,t}^{\pm}$	maximum expanded capacity for electricity-conversion technologies (GW)
$OW_{k,t}^{\pm}$	other type water for electricity-conversion technology (10^6 m^3/TJ)
$PE_t^{\pm}$	imported electricity amounts (GWh)
$\underset{\sim}{PEC}_{k,t}^{\pm}$	purchasing electricity resource cost (10^3 \$/TJ)

$PE\underset{\sim}{J}_t^{\pm}$ importing electricity cost (10^3 \$/GWh)

$RC_{k,t}^{\pm}$ residual capacity for electricity-conversion technologies (GW)

$ST_{k,t}^{\pm}$ service time of electricity-conversion technologies (h)

$S\underset{\sim}{U}_{k,t}^{\pm}$ financial subsidy (10^3 \$/GWh)

$TAW_t^{\pm}$ amount of available water resource (10^6 m^3)

$TE_{k,t}^{\pm}$ power-facilities conversion efficiency (%)

$VE\underset{\sim}{C}_{k,t}^{\pm}$ variable cost for electricity expansion (10^3 \$/GW)

$VG\underset{\sim}{C}_{k,t}^{\pm}$ variable cost for generating electricity (10^3 \$/GWh)

$WDB_t^{\pm}$ water resources demand (10^6 m^3)

$YC_{k,t}^{\pm}$ 0-1 variables for electricity-generation

$ZL_{k,t}^{\pm}$ power consumption rate (%)

Declaration of Interest Statement

All of the authors have read and approved the paper and it has not been published previously nor is it being considered by any other peer-reviewed journal. No conflict of interest.