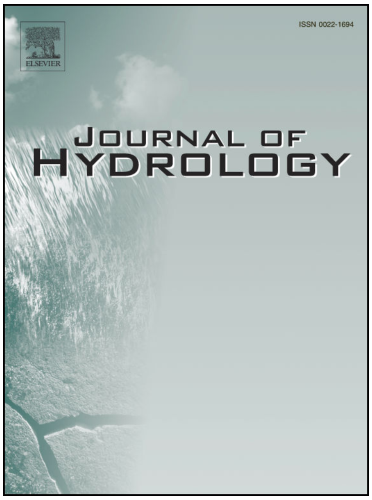

Research papers

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# Coupling the two-level programming and Copula for optimizing energy-water nexus system management – A case study of Henan Province

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## Abstract

The management of water resources system and energy system belongs to different decision-making departments, and there is a certain hierarchical relationship between them. Optimizing the configuration of regional-scale water and energy systems from a global perspective, and considering the correlations between water resources shortage risk and energy shortage risk as well as their joint-risk interaction, can improve the accuracy and efficiency of management decisions. This study aims to propose a copula-based interval two-level programming (CITP) method by integrating a copula-based interval stochastic programming (CISP) method and two-level programming (TP) method. CITP can not only balance the goals and preferences among different decision-making levels but also analyze the risk interactions between water resources availability and electricity demand. The CITP method is then applied to planning the energy-water nexus system (EWNS) of Henan Province (China), where various decision-making levels and diverse risk-interaction scenarios are analyzed. Results reveal that: during the planning horizon, a) the total electricity-generation amounts can change by $7.31 \times 10^3$ GWh from S1 to S5; b) the future electricity-supply structure will toward a more sustainable aspect, and the electricity generated from gas-fired, hydro and wind power can increase by $6.2 \times 10^3$ GWh, $3.7 \times 10^3$ GWh and $5.8 \times 10^3$ GWh, respectively. Results can provide decision supports for the coordinated development of regional-scale EWNS management among water, energy, economy and society as well as environment.

**Keywords:** copula, energy-water nexus system, planning, risk interactions, two-level programming, uncertainty

## 1. Introduction

### *1.1 Significance*

Energy and water are closely linked and restrict each other, which has become increasingly indispensable for maintaining the world's sustainable development [1]. With the increase of population and the acceleration of urbanization, resources and environment have become the main problems constraining regional sociometric development. To some extent, the growing demands of water and energy put many cities at a risk of water and energy shortages [2]. Moreover, the world's energy and water resources demands will respectively increase by 80% and 55% in 2050 compared to 2015 [3]. This has become an important bottleneck for the world's sustainable development, presenting a series of realistic problems and administrative difficulties to local decision makers [4]. Thus, it is of great importance to efficaciously solve the trade-off between water shortage and energy security, and jointly plan the future energy system management by low-carbon energy consumption and high-efficiency water utilization. Nexus is an instructive approach to settle multifarious complicated problems which combine water and energy collectively, therefore it could be diffusely applied to the regional-scale energy system research [5, 6]. However, there are many complex interrelationships in the real-world energy-water nexus system (EWNS) management [7-9].

### *1.2 Complexity and uncertainty*

The complexity and uncertainty of EWNS include: a) water is used for cleaning, cooling and conducting whole process of energy production from mineral exploitation to electricity generation, while energy is used for water supply, transportation and treatment [10]; besides, energy and water act upon each other, resulting in the synergic risk in EWNS [2, 11]. b) in EWNS management, varying energy and water-resources utilization processes associated with changed energy and water resources availabilities, dynamic energy and water resources demands, estimated economic data, as well as subjective decisions for environmental impacts control need to be addressed jointly [12]. c) the exsiting energy and water resources managers are independent of each other, leading to the management of EWNS to be fragmented not in a synergic way [13]. d) EWNS management includes various decision makers, and each decision maker may formulate conflicting decisions toward its own preferences [14].

### *1.3 Literature review*

Previously, numerous studies such as life cycle assessment (LCA), input-output (IO) model, ecological network analysis (ENA), system dynamic modelling (SDM), agent-based modelling (ABM) and integrated water resources or energy system model were proposed for quantitatively analyzing ENWS [15-19]. Moreover, many researchers have conducted for handling associated complexities and uncertainties related to stochastics variables (e.g., rdandom water-resources availability, electricity demand and their complex interactions), interval system coefficients (e.g., water-consumption parameters, pollutant-emission coefficients and technical parameters) and the hierarchically conflicting objectives (e.g., the objectives of minimum system cost and minimum water consumption) in the EWNS [2, 9, 12, 14, 20-23]. For example, Cai et al. [2] used an integrated approach (IA) for assessing interactive risk in water and energy resources. Lv et al.

[12] proposed an integrated optimization method to plan the EWNS, in which uncertainties of interval- and random information were solved. Zhang and Vesselinov [14] proposed a two-level model (TLM) for addressing the tradeoffs between upper-level and lower-level managers (i.e. energy-development manager and whole-system manager) in EWN management. Li et al. [23] proposed a coalescent multi-objective programming (MOP) method which could be used to manage the energy-water-food nexus (EWFN) in agriculture, as well as deal with the contradictions in water, energy, food and land.

Although LCA, IO, ENA, SDM and ABM were effective for quantitatively analyzing ENWS, while most of them focused on deterministic analyses, which could encounter difficulties in reflecting complexities and uncertainties existed in EWNS. Furthermore, the TLM proposed by Zhang and Vesselinov [14] and MOP proposed by Li et al. [23] are effective for dealing with the tradeoffs in two-level decision makers or different objectives, while they are incapable of handling the random water-resources availability and electricity demand as well as the system joint risk caused by their complex interactions. The IFCCP proposed by Lv et al. [12] and IA proposed by Cai et al. [2] can effectively deal with stochastic variables and interval values as well as the stochastic variables' joint interactions employed to the EWNS; however, the IFCCP are based on assumptions that all of random variables employed to probabilistic constraints are normally and independently distributed, and the relationship among random variables are linear, leading to a narrower feasible region than the actual interval solutions. Moreover, IFCCP and IA both can hardly coordinate the tradeoffs among different decision makers or policies. Thus, it is of indispensability to exploit more robust optimization techiques that integrate the advantages of TLM, MOP, IFCCP and IA into one approach for jointly addressing the associated complexities and uncertainties in EWNS management problems.

### *1.4 Innovation*

This study aims to formulate a two-level based copula interval-stochastic programming (TCIP) approach to manage the regional-scale EWNS issues. TCIP integrates the superiority of TLM, MOP, IFCCP and IA into a framework, which can not only balance the goals and preferences among different decision-making levels but also analyze the risk interactions between water resources availability and electricity demand through using copula functions even having different probability distributions and previously unknown correlations.Then, the TCIP is applied to Henan Province, China. Two-level managers (i.e. the upper-levlel manager for the water resources-development and the lower-level manager for the whole-system) and five scenarios with different groups of water resources availability and electricity consumption are considered. Results will provide supports for: a) identifying the desired electricity- supply patterns under the conflicts among economic objective, water resources shortage, electricity demand, as well as environmental requirement, b) balancing the conflicts toward the two-level managers' own attitudes; c) analyzing interactions between water resources availability and electricity consumption, and disclosing their joint risk on EWNS under different scenarios.

## **2. Methodology**

A general two-level programming (TP) problem is [24]:

$$\underset{x_1}{Min}\, F\left(x_1, x_2\right) \qquad (1a)$$

where $x_2$ is obtained by:

$$\underset{x_2}{Min}\, f(x_1, x_2) \tag{1b}$$

subject to:

$$G = \left\{ \left( x_1, x_2 \right) \middle| g_i \left( x_1, x_2 \right) \le 0,\ i = 1, 2, ..., m,\ \ x_1, x_2 \ge 0 \right\} \tag{1c}$$

where $x_1 \in R^{n1}$ (upper-level variables) and $x_2 \in R^{n2}$ (lower-level variables); $F : R^{n1} \times R^{n2} \to R$, $f : R^{n1} \times R^{n2} \to R$ are the corresponding objective functions. $G$ is the constraint. The solution process of TP problem can be solved based on the leader-follower Stackelberg game by using the fuzzy approach [25].

Although TP can effectively deal with conflicts by diverse decision-making levels while it can hardly handle uncertain parameters presented as interval values owing to the observation error and subjective estimation [26]. It is also incapable of tackling multiple random variables as well as analyzing their associated interactions [27]. Actually, there are many other approaches to reflect the co-effect among different random variables such as the joint-probabilistic programming (JPP) methods [28, 29]. However, the conventional JPP methods are based on the assumptions that all of random variables existing in chance-constraints are normally and independently distributed [30, 31], and they can merely reflect linear dependence of various random variables while incapable of reflecting nonlinear dependence [32]. As an improvement of JPP, the copula-based interval stochastic programming (CISP) can solve the above problems with a complex relationship (including nonlinear dependence) [32]. A general CISP method is [30, 31, 33]:

$$\text{Min } E^{\pm} = \sum_{j=1}^{n} c_j^{\pm} x_j^{\pm} \tag{2a}$$

subject to:

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

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

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

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

where $a_{ij}^{\pm} \in \left\{R^{\pm}\right\}^{m\times n}, b_i^{\pm} \in \left\{R^{\pm}\right\}^{m\times 1}, c_j^{\pm} \in \left\{R^{\pm}\right\}^{1\times n}, x_j^{\pm} \in \left\{R^{\pm}\right\}^{n\times 1}$; $R^{\pm}$ means interval numbers; $C$ is the determinate copula; $p_i\ (i = 1, 2, ..., k)$ are probability-violation levels of the chance constraints (2b); $b_i^{p_i} = F_i^{-1}(p_i)$.

Through integrating CISP into TP, a TCIP method is developed as:

$$\underset{x_1}{Min}\, F^{\pm}\left(x_1^{\pm}, x_2^{\pm}\right) = \sum_{j=1}^{n} c_j^{\pm} x_{1j}^{\pm} \tag{3a}$$

$$\underset{x_2}{Min}\, f^{\pm}(x_1^{\pm}, x_2^{\pm}) = \sum_{j=1}^{n} d_j^{\pm} x_{2j}^{\pm} \tag{3b}$$

subject to:

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

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

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

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

$$G^{\pm} = \left\{ \left( x_1^{\pm}, x_2^{\pm} \right) \middle| g_i \left( x_1^{\pm}, x_2^{\pm} \right) \le 0, i = 1, 2, ..., m,\ x_1^{\pm}, x_2^{\pm} \ge 0 \right\} \tag{3g}$$

The solution theory of TCIP method is based on Sakawa et al. [34], Pramanik and Roy [35] and Huang et al. [36], by seeking the maximum overall satisfactory degree in a computation-effective way.

## 3. Case Study

### *3.1 Problem statement*

Henan province is located in the middle and lower reaches of the Yellow River (China), occupying an area of 167 × $10^3$ $km^2$. There are 17 prefectural-level cities and 1 provincial capital under the jurisdiction of Henan province with the total population of 108.5 million and an annual growth rate of 7.8% of the gross domestic production (GDP) by year of 2017.As the rapid growth of population and the sustainable development in economy, the electricity demand for social production and people's life has been increasing persistently. The main goals listed in the 13th Five-year (i.e. years 2016-2020) Energy Development Plan of Henan Province are as follows: the total energy consumption should be controlled within 267 million tonnes of standard coal, the total electricity consumption of the whole society should be about 376 billion KWh, and the total installed power capacity should reach 87 million KW by the year of 2020 [37].

Meanwhile, the water consumption situation is not optimistic. According to Water Resources Bulletin of Henan province in 2017, the total amount of water resources was 42.31 billion $m^3$ while the total water consumption amount reached 23.38 billion $m^3$, which indicated that a shortage of water resources occurred in recent years to some extent [38]. In addition, there was an increasing demand of environment protection due to public attention to environmental issues and implementation of national environmental protection policies. According to the 13th Five-year Plan of Henan Province for Ecological and Environmental Protection, the reduced sulfur dioxide ($SO_2$) and nitrogen oxides ($NO_x$) emissions should be 205 and 158 thousand tonnes by 2020, respectively [39].

### *3.2 TCIP-EWNS modeling formulation*

For a provincial TCIP-EWNS model, various elements were considered in relation to some uncertainties, as detailed in Figure 1. For instance, some technical and economic parameters were expressed as interval values, while water resources availability and electricity demand were represented by probability distributions. The TCIP-EWNS model is then applied to Henan Province, China. The TCIP-EWNS model aims at minimizing the system cost while at the same time initially addressing the water-consumption target, which mainly includes cost of water resources for electricity generation, cost for purchasing energy resources, costs for electricity generation, electricity import and electricity transmission, as well as contamination controlling. The constraints consist of water- and energy-resources availability, electricity demand-supply security, power plant output limitation, environmental emission control, 0-1 variables and nonnegative constraints.

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Place Figure 1 here

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The objective function of upper decision-making level is:

$$\mathrm{Min}\, W^{\pm} = \sum_{k=1}^{2} EGA_{k,t}^{\pm} \times \left( CW_{k,t}^{\pm} + BW_{k,t}^{\pm} + DW_{k,t}^{\pm} \right) + \sum_{k=3}^{6} EGA_{k,t}^{\pm} \times OW_{k,t}^{\pm} \tag{4}$$

The constraints are:

(1) *System joint-risk constraint between water resources availability and electricity demand:*

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

(2) *Water resources availability constraint:*

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

(3) *Constraint for electricity demand-supply security:*

$$\Pr\left\{ \left( \sum_{k=1}^{6} EGA_{k,t}^{\pm} \times \left(1 - ZL_{k,t}^{\pm}\right) \times TE_{k,t}^{\pm} + PE_t^{\pm} \right) \times \left(1 - \eta_t^{\pm}\right) \ge EDB_t^{\pm} \right\} \ge 1 - p_2 \tag{7}$$

(4) *Power plant output limitation constraint*:

$$EGA_{k,t}^{\pm} \le \left( RC_{k,t=0}^{\pm} + \sum_{t=0}^{t-1} EC_{k,t}^{\pm} \right) \times ST_{k,t}^{\pm} \tag{8}$$

(5) *Nonnegative constraints:*

$$EGA_{k,t}^{\pm},\ PE_t^{\pm},\ EC_{k,t}^{\pm} \geq 0 \tag{9}$$

The objective function of the lower decision-making level is:

$$\text{Min } F^{\pm} = (1)+(2)+(3)+(4)+(5)+(6)+(7)+(8) \tag{10a}$$

(1) *Cost of water resources for electricity generation:*

$$\begin{aligned}&\sum_{k=1}^{2}\sum_{t=1}^{6} EGA_{k,t}^{\pm}\times\left(CCW_{k,t}^{\pm}\times CW_{k,t}^{\pm}+CBW_{k,t}^{\pm}\times BW_{k,t}^{\pm}+CDW_{k,t}^{\pm}\times DW_{k,t}^{\pm}\right)\\&+\sum_{k=3}^{6}\sum_{t=1}^{6} EGA_{k,t}^{\pm}\times COW_{k,t}^{\pm}\times OW_{k,t}^{\pm}\end{aligned} \tag{10b}$$

(2) *Cost for purchasing energy resources:*

$$\sum_{k=1}^{2}\sum_{t=1}^{6} PEC_{k,t}^{\pm}\times EGA_{k,t}^{\pm}\times FE_{k,t}^{\pm} \tag{10c}$$

(3) *Cost for importing electricity:*

$$\sum_{i=1}^{6} PEJ_t^{\pm}\times PE_t^{\pm} \tag{10d}$$

(4) *Electricity generation cost:*

$$\sum_{k=1}^{6}\sum_{t=1}^{6}\left(EGA_{k,t}^{\pm}\times VGC_{k,t}^{\pm}\right)+\sum_{k=1}^{6} FGC_{k,t}^{\pm}\times\left(RC_{k,t=0}^{\pm}+\sum_{t=1}^{6} EC_{k,t}^{\pm}\right) \tag{10e}$$

(5) *Capacity expansion cost:*

$$\sum_{k=1}^{6}\sum_{t=1}^{6}\left(FEC_{k,t}^{\pm}\times YC_{k,t}^{\pm}+VEC_{k,t}^{\pm}\times EC_{k,t}^{\pm}\right) \tag{10f}$$

(6) *Cost for electricity transmission:*

$$\sum_{k=1}^{6}\sum_{t=1}^{6} EGA_{k,t}^{\pm} \times CU_{k,t}^{\pm} \tag{10g}$$

(7) *Cost for pollutant reduction*:

$$\sum_{k=1}^{6}\sum_{t=1}^{6}\sum_{q=1}^{3} EGA_{k,t}^{\pm} \times \left(3.6 \times CP_{t,q}^{\pm} + CE_{t,q}^{\pm} / ST_{k,t}^{\pm} - 3.6 \times SU_{t}^{\pm}\right) \tag{10h}$$

(8) *Cost for CO$_2$ mitigation:*

$$\sum_{k=1}^{6}\sum_{t=1}^{6} EGA_{k,t}^{\pm} \times \delta_{k,t}^{\pm} \times \mu_{k,t}^{\pm} \tag{10i}$$

The constraints are:

(1) *System joint-risk constraint between water resources availability and electricity demand:*

$$C\left(1-p_1, 1-p_2\right) = 1-p \tag{11}$$

(2) *Water resources availability constraint:*

$$\Pr\left\{\sum_{k=1}^{2} EGA_{k,t}^{\pm} \times \left(CW_{k,t}^{\pm} + BW_{k,t}^{\pm} + DW_{k,t}^{\pm}\right) + \sum_{k=3}^{6} EGA_{k,t}^{\pm} \times OW_{k,t}^{\pm} \le TAW_{t}^{\pm}\right\} \ge 1-p_1 \tag{12}$$

(3) *Constraint for electricity demand-supply balance:*

$$\Pr\left\{\left(\sum_{k=1}^{6} EGA_{k,t}^{\pm} \times \left(1-ZL_{k,t}^{\pm}\right) \times TE_{k,t}^{\pm} + PE_{t}^{\pm}\right) \times \left(1-\eta_{t}^{\pm}\right) \ge EDB_{t}^{\pm}\right\} \ge 1-p_2 \tag{13}$$

(4) *Energy resource availability constraint:*

$$EGA_{k,t}^{\pm} \times FE_{k,t}^{\pm} \le AR_{k,t}^{\pm} \tag{14}$$

(5) *Power plant output limitation constraint*:

$$EGA_{k,t}^{\pm} \le \left(RC_{k,t=0}^{\pm} + \sum_{t=0}^{t-1} EC_{k,t}^{\pm}\right) \times ST_{k,t}^{\pm} \tag{15}$$

(6) *Constraint for water demand-supply balance:*

$$\sum_{k=1}^{2} EGA_{k,t}^{\pm} \times \left( CW_{k,t}^{\pm} + BW_{k,t}^{\pm} + DW_{k,t}^{\pm} \right) + \sum_{k=3}^{6} EGA_{k,t}^{\pm} \times OW_{k,t}^{\pm} \geq WDB_{t}^{\pm} \tag{16}$$

(7) *Constraint for pollutant emissions:*

$$\sum_{k=1}^{6} EGA_{k,t}^{\pm} \times AMR_{k,t,q}^{\pm} \leq ES_{t,q}^{\pm} \tag{17}$$

(8) *Constraint for $CO_2$ emission:*

$$\sum_{k=1}^{6} EGA_{k,t}^{\pm} \times \delta_{k,t}^{\pm} \times \left( 1 - CCA_{t}^{\pm} \right) \leq ESC_{t}^{\pm} \tag{18}$$

(9) *0-1 variables and maximum capacity-expansion limitation:*

$$YC_{k,t}^{\pm} \begin{cases} = 1; & \text{if capacity expasion is undertaken} \\ = 0; & \text{if otherwise} \end{cases} \tag{19a}$$

$$0 \leq EC_{k,t}^{\pm} \leq MC_{k,t}^{\pm} \times YC_{k,t}^{\pm} \tag{19b}$$

(10) *Nonnegative constraints:*

$$EGA_{k,t}^{\pm},\ PE_{t}^{\pm},\ EC_{k,t}^{\pm} \geq 0 \tag{20}$$

### *3.3 Data acquisition*

In this study, nomenclatures for parameters and variables are depicted in Appendix A. Relevant technical and economic parameters were obtained from the Statistical Yearbook of Henan Province, the 13th Five-year Energy Development Plan of Henan Province, and other parameters were obtained from the government work report of Henan province and related published articles [7, 12, 14, 37-41]. For instance, the correlative water-consumption parameters (e.g., water consumption for cooling system, steam system, desulfurization system and other systems) that are presented as interval values were obtained from published papers by Liu et al. [7], Lv et al. [12], Zhang and Vesselinov [14]. The electricity-generation costs which are closely related to the volatility of interest rates, inflation rates and other factors (i.e., energy price, labor fee, and operation condition) were collected from the related papers by Yu et al. [30, 42]. Water resources availability and electricity demand which are affected by meteorologic, hydrologic and sociometric conditions were presented as random variables [7, 12, 43-46]. Table 1 illustrates the historical amounts of electricity consumption and annual growth rate of electricity consumption in Henan Province, which were obtained by Statistical Yearbook of Henan Province [40]. Since the P values of marginal distribution functions of water resources availability and electricity consumption were both larger than 0.05, indicating Normal distribution could fit well for the marginal distributions of them by using Kolmogorov-Smirnov test [47]. Pearson's linear correlation tests were used for confirming the random variables if they were mutually correlated. The $R^2$ between water resources availability and electricity consumption in industry during years of 2013-2024 was 0.699, which indicated that water resources availability and electricity consumption have high correlation. In this study, Frank copula was selected to model the joint distribution of water resources availability and electricity consumption owing to its smallest RMSE and MSE values [48].

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Place Table 1 here

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Besides, five scenarios with different groups of water resources-availability violation level ( $p_1$ ) and electricity-consumption violation levels ( $p_2$ ) were considered for analyzing interactions between water resources availability and electricity consumption, and disclosing their joint risk ( $p$ ) on EWNS under different scenarios. The selected five scenarios for joint and individual constraint-violation levels $\left(p, p_1, p_2\right)$ were (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, 0.2, 0.1) from scenario 1 to scenario 5 (abbreviated as S1, S2, S3, S4 and S5), respectively (as shown in Table 2). In addition, three levels of decision makers were considered. In detail, the upper level model (ULM) mainly focuses on the minimum water consumption in the electricity generation; the lower level model (LLM) aims at achieving the maximum economic benefit under series of water resources availability, energy resource availability and other constraints; the two-level model (TLM) focuses on obtaining the maximum economic benefit while the water-consumption target initially be addressed.

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Place Table 2 here

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## 4. Result Analysis

### *4.1 Electricity generation and water consumption*

Henan province has achieved a GDP of 4,805.59 billion RMB ¥ by 2018, and the rapid progress in economy brings a greater demand of electricity generation. Figure 2 presents the electricity-generation pattern in different scenarios under TL. Generally, different scenarios would generate diverse electricity-generation schemes. For example, the total electricity-generation amounts under TL would change from $190.3\times10^3$ GWh (S1) to $197.9\times10^3$ GWh (S5) in year 1. This is because lower available water resources would force decision makers to select more renewable energies having lower water requirement; conversely, at a higher water resources-availability level, more fossil energies would be firstly chosen owing to the lower investment. Besides, the total supplied electricity would go ascend with time corresponding to the increasing electricity demand and local government development plans. In detail, during the whole planning horizon, the coal-fired power generation would decrease by $0.9\times10^3$ GWh; while the electricity generated from gas-fired, hydro and wind power during the planning horizon would increase by $6.2\times10^3$ GWh, $3.7\times10^3$ GWh and $5.8\times10^3$ GWh, respectively. Results implied that the future electricity supply structure would toward a more sustainable aspect that balanced the conflicts of water availability, electricity supply security, environmental requirement and economic cost, as well as hierarchical concerns of different decision makers.

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Place Figure 2 here

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Increasing electricity generation results in growing demand of water resources. Figure 3 presents the scheme of water consumption in diverse scenarios under TL. For example, coal-fired power in TL consumed 95.06% (S1) and 94.93% (S2) of the water consumption, respectively. This is because different groups of water resources availability and electricity demand scenarios were considered, and the interactions between water resources availability and electricity demand could influence the water consumption's structure. As the joint and individual constraint-violation levels of S1 and S2 were (0.1, 0.02, 0.2) and (0.1, 0.1, 0.3188), respectively, the electricity demand of S1 was higher than that in S2 although the decision-maker of S1 could obtain less water resources availability. All these factors forced the decision-maker of S1 to choose fossil energy with higher water consumption but lower electricity generation cost. Meanwhile, for every electricity-conversion technology, coal-fired power consumed the most of water, followed by gas-fired power, hydro power and others, among which wind power consumed no water resources. And water consumption by various electricity conversion technology showed disparate tendency with time. In detail, water consumption by coal-fired was decreasing while the others (including gas-fired, hydro, solar and biomass) were increasing. Therefore, in the long time, water consumption in the power sector could be reduced, and the proportion of clean energy in power industry would be increasing corresponding to the whole society's energy saving and pollution reduction.

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Place Figure 3 here

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*4.2 Electricity supply*

With the rapid economic and social development of Henan province, the electricity demand is increasing at the same time, leading to the increment of capacity expansion. Figure 4 presents the results of expanded capacities from different electricity conversion technologies under various decision-making levels. Generally, the expanded capacities of each conversion technology would be disparate under various decision-making levels. For hydro power, the expanded capacities would be 0.39 GW under TL and 0.44 GW under LL, respectively. This is because there were more water resources availability constraints under TL compared to LL, resulting in fewer local electricity generation and more capacity expansions. Besides, the expanded capacity of various electricity conversion technology would change with time corresponding to the increasing electricity demand and local government development plans. In addition, there was no expansion plans in coal-fired power while wind power had the highest expansion scheme over changing periods. This is because decision makers would incline to choose local electricity generation having lower water-consumption and pollutant-discharge. Results indicated that energy managers would tend to enlarge local renewable energies to ensure the security of local power industry and promote the sustainable development of district in the long run.

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Place Figure 4 here

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It is indispensable to import electricity when the electricity generation cannot satisfy the electricity demand of Henan Province. At the present situation, the imported electricity took nearly 40% of the entire power structure, which was a pretty big part of power industry. Generally, the imported electricity would be disparate under different decision-making levels (as shown in Figure 5). For example, the imported electricity under LL and UL would be respectively [176.4, 192.7] × $10^3$ GWh and [190.5, 202.5] × $10^3$ GWh in year 1 under S1; while the imported electricity under TL would be [188.6, 201.6] × $10^3$ GWh. This is because the UL decision makers would tend to import more electricity in order to reduce water resources consumption while the LL decisions makers would incline to purchase less electricity for reducing the system cost. Therefore, the TL model could provide compromised optimization solutions between economic cost and water resources consumption. In addition, the imported electricity would decrease with time with the consideration of power security and system reliability.

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Place Figure 5 here

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## 4.3 Emissions of $CO_2$ and pollutants

Results indicate that the amounts of carbon dioxide ($CO_2$) emissions under TL was lower than that in LL (Figure 6). For instance, the $CO_2$ emissions would be [188.6,189.8] $\times 10^6$ tonne under LL and [178.6,184.8] $\times 10^6$ tonne under TL in year 1 under S1, respectively. This is because the electricity generation from coal-fired power (i.e. the primary source of $CO_2$ emission) of LL was less than that in TL. Besides, the emissions of pollutants would also be disparate in various scenarios. As is shown in Figure 7, the amount of $NO_X$ emissions would increase from $296.7\times10^6$ tonne (S1) to $307.4\times10^6$ tonne (S5). This is because different scenarios would affect the electricity-generation pattern and then lead to the variation of pollutant-emission pathway. In addition, a downwards trend of pollutant emissions would be obtained over the planning horizon because of the aspects from government participation, policy stimulation and technology innovation.

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Place Figures 6 and 7 here

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### 4.4 System cost and satisfaction

Figure 8 shows the system cost and satisfaction under different decision-making levels in various scenarios. Results showed that in S1, the system cost would be \$ [3.07, 3.45] × $10^{12}$ under TL and \$ [2.99, 3.39] × $10^{12}$ under LL, respectively. This is because the LL model aims at achieving the minimum system cost while the TL model takes both economic factors and water consumption into consideration. Results implied that the LL was more suitable for providing decision-making reference for the economic managers while the TL model could integrate objectives of different levels to provide a more reasonable optimization solution for decision makers. Besides, the minimum system cost would be obtained in S2 owing to the interactions between water resources availability and electricity demand. Therefore, desired schemes for balancing the tradeoff among water-energy joint risk, environmental control and system cost would be obtained.

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Place Figure 8 here

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## 5. Discussion

### 5.1 Comparison with single level programming approaches (i.e. UL and LL)

Figure 9 illustrates the compared results of electricity generation, capacity expansion, imported electricity and system cost among the UL, TL and LL. Results indicated that values obtained by the TL would be in the range of UL and LL. For instance, as shown in Figure 9a, the electricity generation in year 1 would be 190.3 × $10^3$ GWh under TL, while the values would be 188.6 × $10^3$ GWh under UL and 204.0 × $10^3$ GWh under LL, respectively. Figure 9d shows that the system cost in TL (i.e. \$ [3.07, 3.45] × $10^{12}$) would be higher than that in LLM (i.e. \$ [2.99, 3.39] × $10^{12}$). It is mainly because the single level of decision makers (i.e. UL and LL) only consider one target in the system objective that looks for the minimum water consumption or minimum system cost; while the minimize water consumption takes the priority in the TL, where the conflicts between water consumption and economic cost corresponding to various decision-making levels can be efficaciously solved. Besides, the LL aims at achieving the minimum system cost while the TL takes both economic factors and water consumption into consideration. Therefore, the LL is more suitable for providing decision-making reference for the economic managers while the TL could integrate objectives of different levels to provide a more reasonable optimization solution for decision makers.

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Place Figure 9 here

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*5.2 Comparison with simple optimization methods (i.e. TP, CISP and IPP)*

The study case could turn into a CISP issue when the two-level of decision makers were not considered. Although the system cost in CISP-EWNS model would be lower than that in TCIP-EWNS model (as shown in Figure 10a). However, the CISP-EWNS model could only consider the conflict of interest by economic managers, it neglected the hierarchical conflict of interest from both water resources managers and economic managers. The problem for planning the EWNS could also be handled through TP method by simplifying TCIP-EWNS model without considering joint shortage risk between water resources availability and electricity demand. The system cost would be \$ $3.38 \times 10^{12}$ in TP (as shown in Figure 10a). A higher system cost would be achieved from TP-EWNS than that from TCIP-EWNS. This is because the objective of TP-EWNS is to minimize the system cost without considering the system violation risk. Besides, TP-EWNS can only deal with hierarchical concerns of different decision makers; it has difficulty in addressing the random water-resources availability and electricity demand as well as their joint interactions. For instance, when the joint violation probability level ($p$) is 0.1, the different groups of individual chance-constraint violation levels (i.e. scenarios 1-5) would lead to changed system costs, and the minimum system cost would merely occur in S2 ($p_1 = p_2$). Summarily, some differences among system costs would be generated owing to different marginal probability levels even if at a fixed joint probability level [32, 33]. In other words, there exist a tradeoff between the system cost and marginal probability levels. Therefore, the TCIP approach proposed in this study is superior to TP, CISP and IPP methods, and thereby can be applied to a wider range of problems than the previous studies.

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Place Figure 10 here

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## 6. Conclusions

In this study, a TCIP approach has been exploited by integrating the superiority of TLM, MOP, IFCCP and IA into a framework. TCIP has the advantages of not only dealing with uncertainties having interval, random and fuzzy information as well as the joint-risk interactions associated with multiple correlated random variables, but also handling the compound conflicts existing in the EWNS management in a synergic way by considering different goals and preferences of various decision makers. Compared to single level programming approaches (i.e. UL and LL), TCIP can effectively address the conflicts between water consumption and economic cost in terms of different decision makers and then provide a more reasonable optimization solution for diverse hierarchical decision-making levels. Compared to simple optimization methods (i.e. TP, CISP and IPP), TCIP can not only deal with hierarchical concerns of different decision makers but also address the random water-resources availability and electricity demand as well as their joint-risk interactions, and thereby can be applied to a wider range of problems than the previous studies.

The TCIP has been applied to Henan Province, where solutions of two-level managers and five scenarios are examined. Results reveal that lower available water resources (S1) can force decision makers to select more renewable energies having lower water requirement, while in comparison, at a higher water resources-availability level (S5), more fossil energies can be firstly chosen owing to the lower investment. In detail, during the entire planning horizon, the total electricity-generation amounts under TL can change by 7.31 × $10^3$ GWh from S1 to S5. Results also imply that the future electricity-supply structure will toward a more sustainable aspect that balances the conflicts of water resources availability, electricity supply security, environmental requirement and economic cost, as well as hierarchical concerns of different decision makers. The electricity generated from gas-fired, hydro and wind power under TL during the planning horizon can increase by $6.2 \times 10^3$ GWh, $3.7 \times 10^3$ GWh and $5.8 \times 10^3$ GWh, respectively.

Although the TCIP-EWNS model can formulate effectively compromising strategies for managing the EWNS problems from aspects of different modelling objectives, various managers' attitudes and varied system joint-risk interactions. However, the TCIP-EWNS model can merely examine the nexus between water resources system and energy system, more complex nexus systems such as water-energy-food nexus system or water-energy-food-carbon nexus system should be further analyzed [49, 50]. Besides, the TCIP-EWNS model merely employed small samples for examining the two random variables' correlation and fitting their marginal probability distributions, thus a large number of samples should be further collected in future studies to improve the model's robustness and validity [51, 52].

## Acknowledgements

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**Q.W. Li:** Software, Formal Analysis, Investigation, Data Curation, Writing-Original Draft, Visualization.
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**Y.R. Fan:** Results Verification, Grammars Correction, Writing-Review & Editing.
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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.**

## Highlights:

►A copula-based interval two-level programming (CITP) method is developed.

►CITP is applied to the energy-water nexus system (EWNS) of Henan Province, China.

►It can balance conflicts by diverse levels and reflect the risk interactions.

►Various decision-making levels and diverse risk-interaction scenarios are analyzed.

►Findings can provide decision supports for the coordinated development of EWNS.

## Appendix A. Nomenclatures for parameters and variables

| | |
|---|---|
| $k$ | electricity-conversion technology, including coal, gas, hydro, wind, solar and biomass power |
| $p$ | the joint risk between water resource availability and electricity demand |
| $p_1$ | violation level of water resource availability |
| $p_2$ | violation level of electricity demand |
| $q$ | pollutant type, including $SO_2$, $NO_x$ and $PM_{10}$ |
| $t$ | planning periods (1-6) |
| $\delta_{k,t}^{\pm}$ | $CO_2$ emission coefficient ($10^3$ tonne/GWh) |
| $\mu_{k,t}^{\pm}$ | $CO_2$ emission cost (\$ $10^6$/ $10^3$ tonne) |
| $\eta_t^{\pm}$ | transmission loss in period t (%) |
| $AMR_{k,t,q}^{\pm}$ | pollutant-emission coefficients (tonne/GWh) |
| $AR_{k,t}^{\pm}$ | available energy resource (TJ) |
| $BW_{k,t}^{\pm}$ | boiler water for electricity-conversion technology ($10^3$ $m^3$/GWh) |
| $C$ | the determinate copula function between water resource availability and electricity demand |
| $CE_{t,q}^{\pm}$ | cost for pollutant emission (\$ $10^3$/GW) |
| $CP_{t,q}^{\pm}$ | cost for pollutant control (\$ $10^3$/TJ) |
| $CU_{k,t}^{\pm}$ | cost for electricity transmission (\$ $10^3$/GWh) |
| $CW_{k,t}^{\pm}$ | cooling water for electricity-conversion technology ($10^3$ $m^3$/GWh) |
| $CBW_{k,t}^{\pm}$ | cost for boiler water (\$ /$10^3$ $m^3$) |
| $CCA_t^{\pm}$ | emission reduction rate of $CO_2$ (%) |
| $CCW_{k,t}^{\pm}$ | cost for cooling water (\$ /$10^3$ $m^3$) |
| $CDW_{k,t}^{\pm}$ | cost for desulfurization water (\$ /$10^3$ $m^3$) |
| $COW_{k,t}^{\pm}$ | cost for other water (\$ /$10^3$ $m^3$) |
| $DW_{k,t}^{\pm}$ | desulfurization water for electricity-conversion technology ($10^3$ $m^3$/GWh) |
| $EC_{k,t}^{\pm}$ | expanded capacity for electricity-conversion technology (GW) |
| $EDB_t^{\pm}$ | electricity demand (GWh) |
| $EGA_{k,t}^{\pm}$ | electricity generation amounts (GWh) |

| | |
|---|---|
| $ES_{t,q}^{\pm}$ | allowed amounts of pollutant emission ($10^3$ tonne) |
| $ESC_{t}^{\pm}$ | allowed amounts of $CO_2$ emission ($10^3$ tonne) |
| $F^{\pm}$ | system cost under lower decision-making level (\$ $10^{12}$) |
| $FE_{k,t}^{\pm}$ | energy consumption rate (TJ/GWh) |
| $FEC_{k,t}^{\pm}$ | fixed cost for expanded capacity (\$ $10^3$/GW) |
| $FGC_{k,t}^{\pm}$ | fixed maintenance cost for electricity generation (\$ $10^3$/GW) |
| $MC_{k,t}^{\pm}$ | maximum expanded capacity for electricity-conversion technology (GW) |
| $OW_{k,t}^{\pm}$ | other water for electricity-conversion technology ($10^3$ $m^3$/GWh) |
| $PE_{t}^{\pm}$ | imported electricity (GWh) |
| $PEC_{k,t}^{\pm}$ | cost for purchasing energy resource (\$ $10^3$/TJ) |
| $PEJ_{t}^{\pm}$ | cost for imported electricity (\$ $10^3$/GWh) |
| $RC_{k,t}^{\pm}$ | residual capacity for electricity-conversion technology (GW) |
| $ST_{k,t}^{\pm}$ | service time of electricity-conversion technology (h) |
| $SU_{k,t}^{\pm}$ | financial subsidy (\$ $10^3$/TJ) |
| $TAW_{t}^{\pm}$ | amounts of water resource availability ($10^6$ $m^3$) |
| $TE_{k,t}^{\pm}$ | power-facilities conversion efficiency (%) |
| $VEC_{k,t}^{\pm}$ | variable cost for expanded capacity (\$ $10^3$/GW) |
| $VGC_{k,t}^{\pm}$ | variable cost for electricity generation (\$ $10^3$/GWh) |
| $W^{\pm}$ | water consumption under upper decision-making level ($10^6$ $m^3$) |
| $WDB_{t}^{\pm}$ | water demand ($10^6$ $m^3$) |
| $YC_{k,t}^{\pm}$ | 0-1 variables for capacity expansion |
| $ZL_{k,t}^{\pm}$ | power consumption rate (%) |

Table 1. The historical amounts of electricity consumption and annual growth rate of electricity consumption in Henan Province

| Year | Electricity consumption ($10^3$ GWh) | Annual growth rate of electricity consumption (%) |
|---|---|---|
| 2007 | 195.7 | — |
| 2008 | 214.0 | 9.3 |
| 2009 | 224.5 | 4.9 |
| 2010 | 254.6 | 13.4 |
| 2011 | 287.3 | 12.8 |

| | | |
|---|---|---|
| 2012 | 298.0 | 3.7 |
| 2013 | 316.8 | 6.3 |
| 2014 | 323.2 | 2.0 |
| 2015 | 315.8 | -2.3 |
| 2016 | 321.6 | 1.8 |
| 2017 | 342.9 | 6.6 |

Table 2. Selected values of joint cumulative probability and marginal probability levels as well as corresponding values of random variables

| Scenarios | Joint cumulative probability | Marginal probability of water resources availability | Marginal probability of electricity consumption | Water resources availability ($10^6$ $m^3$) | Electricity consumption ($10^3$ GWh) | $(p, p_1, p_2)$ |
|---|---|---|---|---|---|---|
| S1 | 0.900 | 0.980 | 0.800 | 317.05 | 322.92 | (0.1, 0.02, 0.2) |
| S2 | 0.900 | 0.900 | 0.6812 | 349.19 | 315.46 | (0.1, 0.1, 0.3188) |
| S3 | 0.900 | 0.8937 | 0.8937 | 350.65 | 331.06 | (0.1, 0.1063, 0.1063) |
| S4 | 0.900 | 0.850 | 0.8999 | 359.39 | 331.75 | (0.1, 0.15, 0.1001) |
| S5 | 0.900 | 0.800 | 0.900 | 367.50 | 331.76 | (0.1, 0.2, 0.1) |

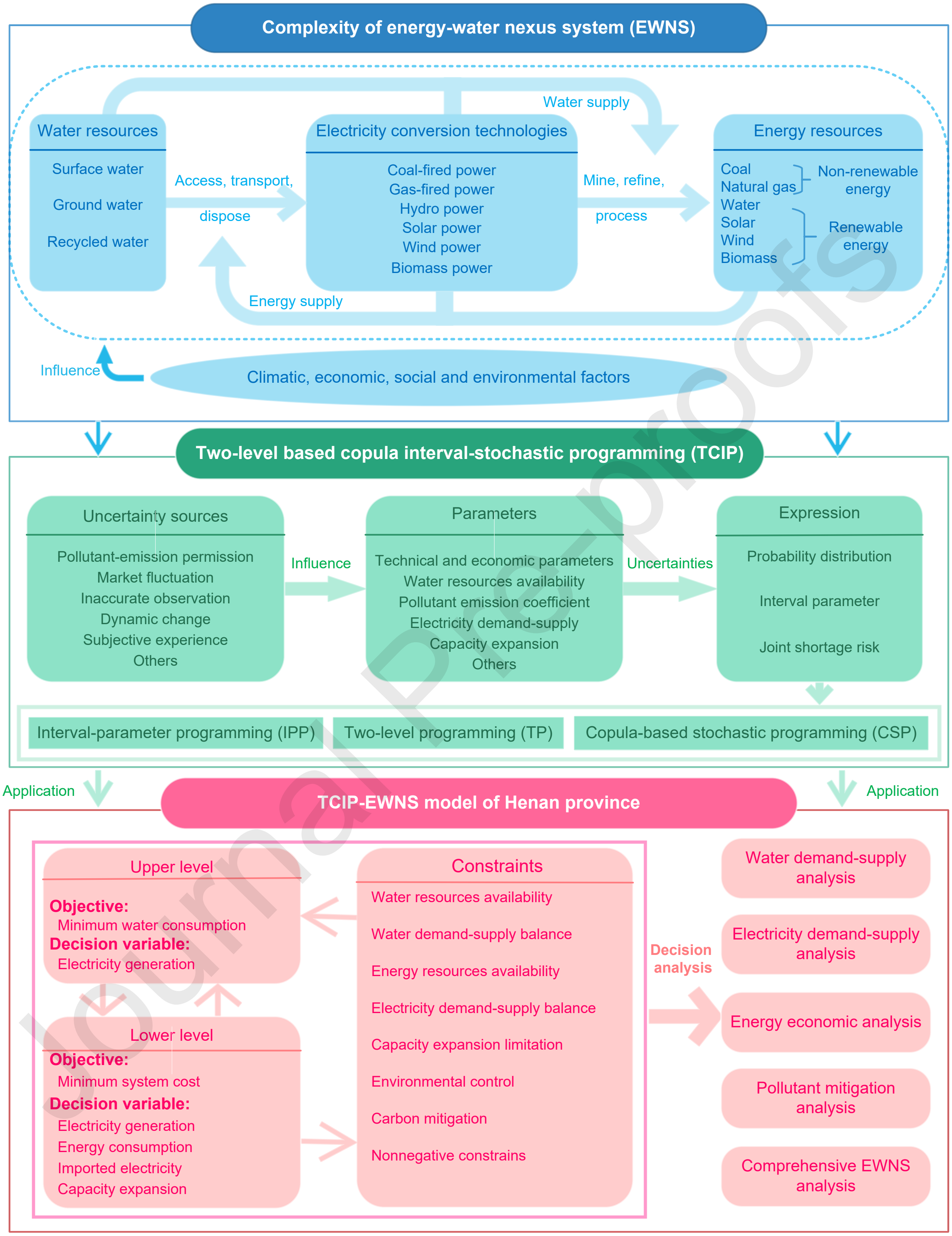


Figure 1. The framework of TCIP-EWNS model

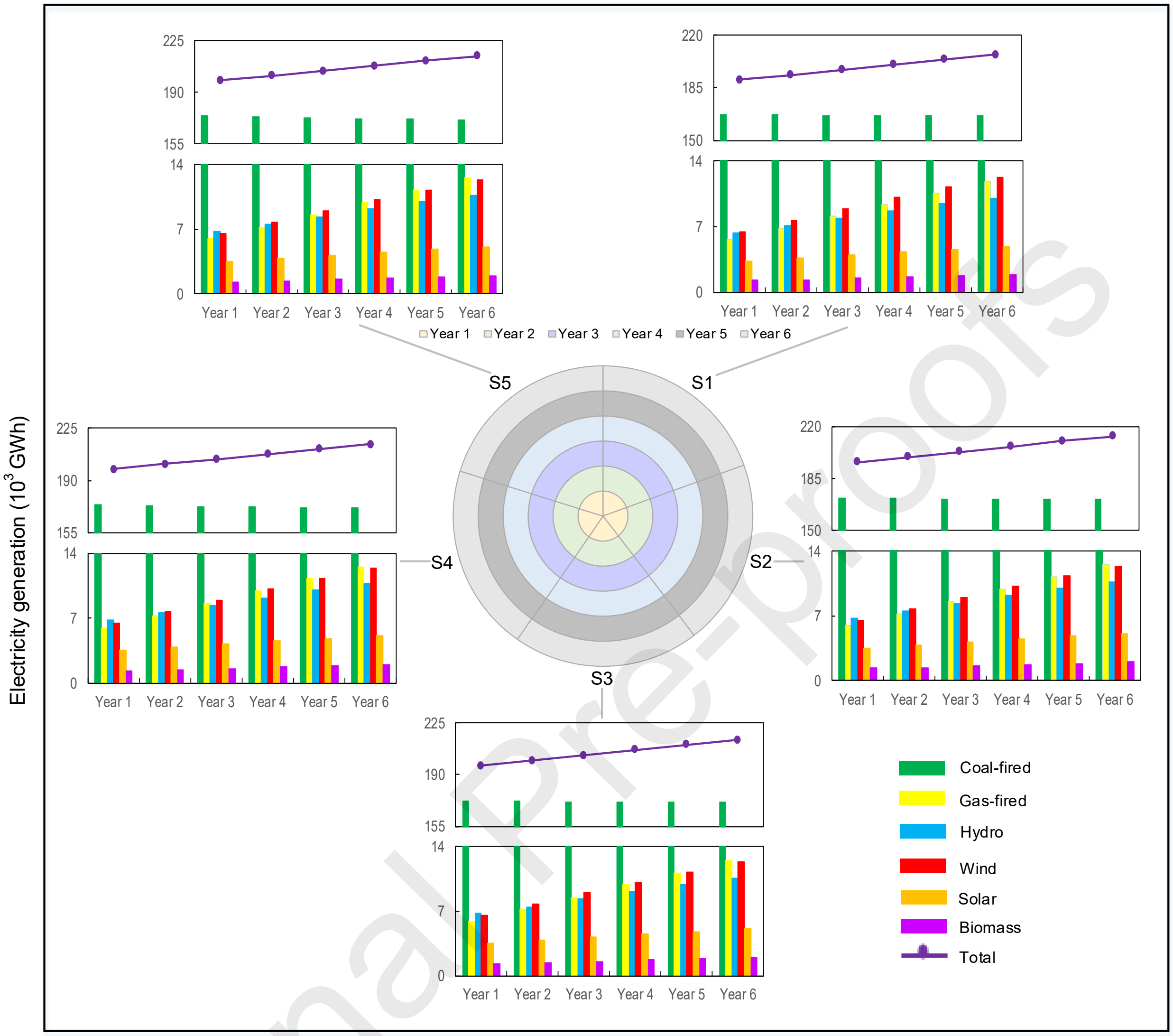


Figure 2. Electricity generation pattern under TL ($10^3$ GWh)

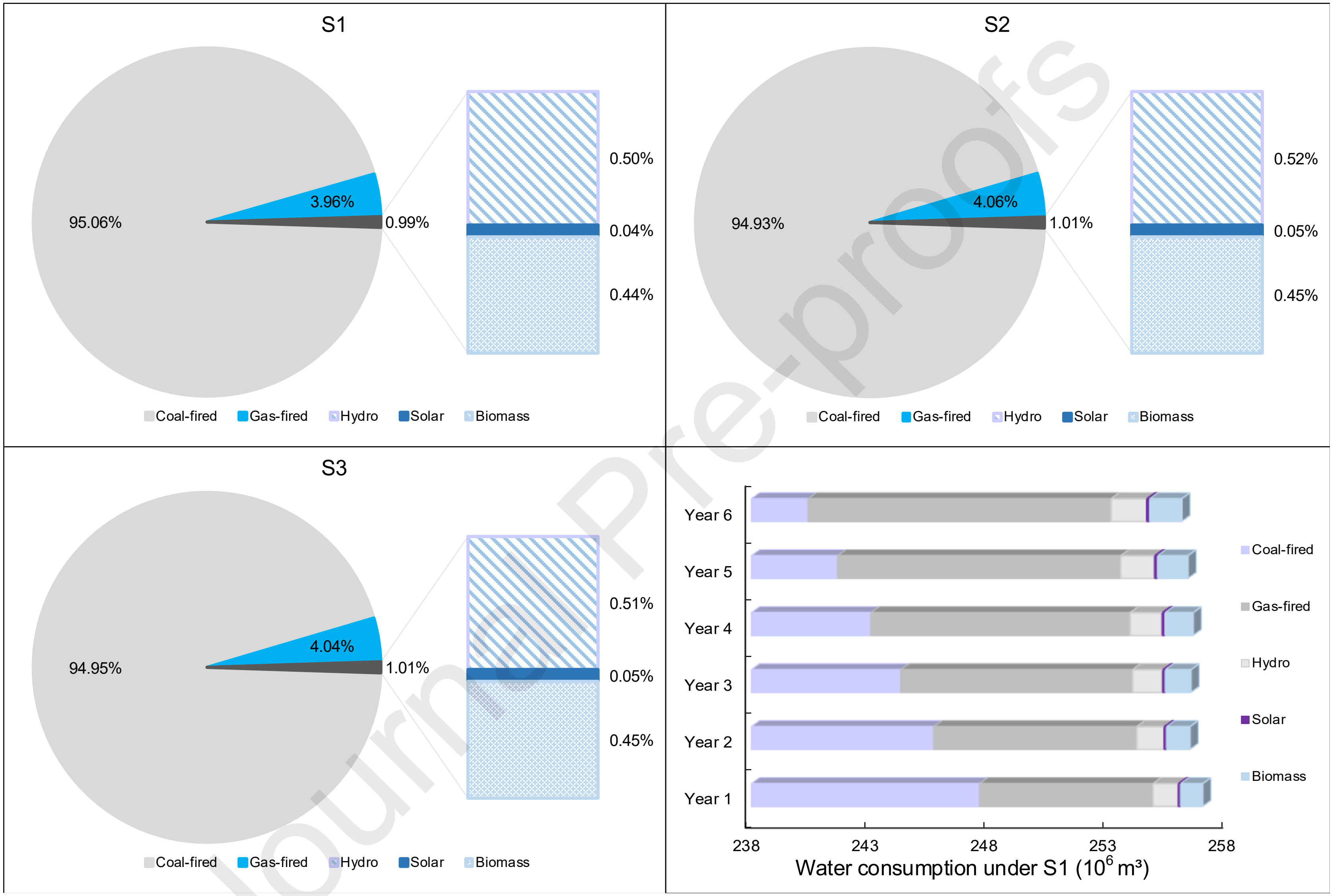


Figure 3. Water consumption scheme under TL (%)

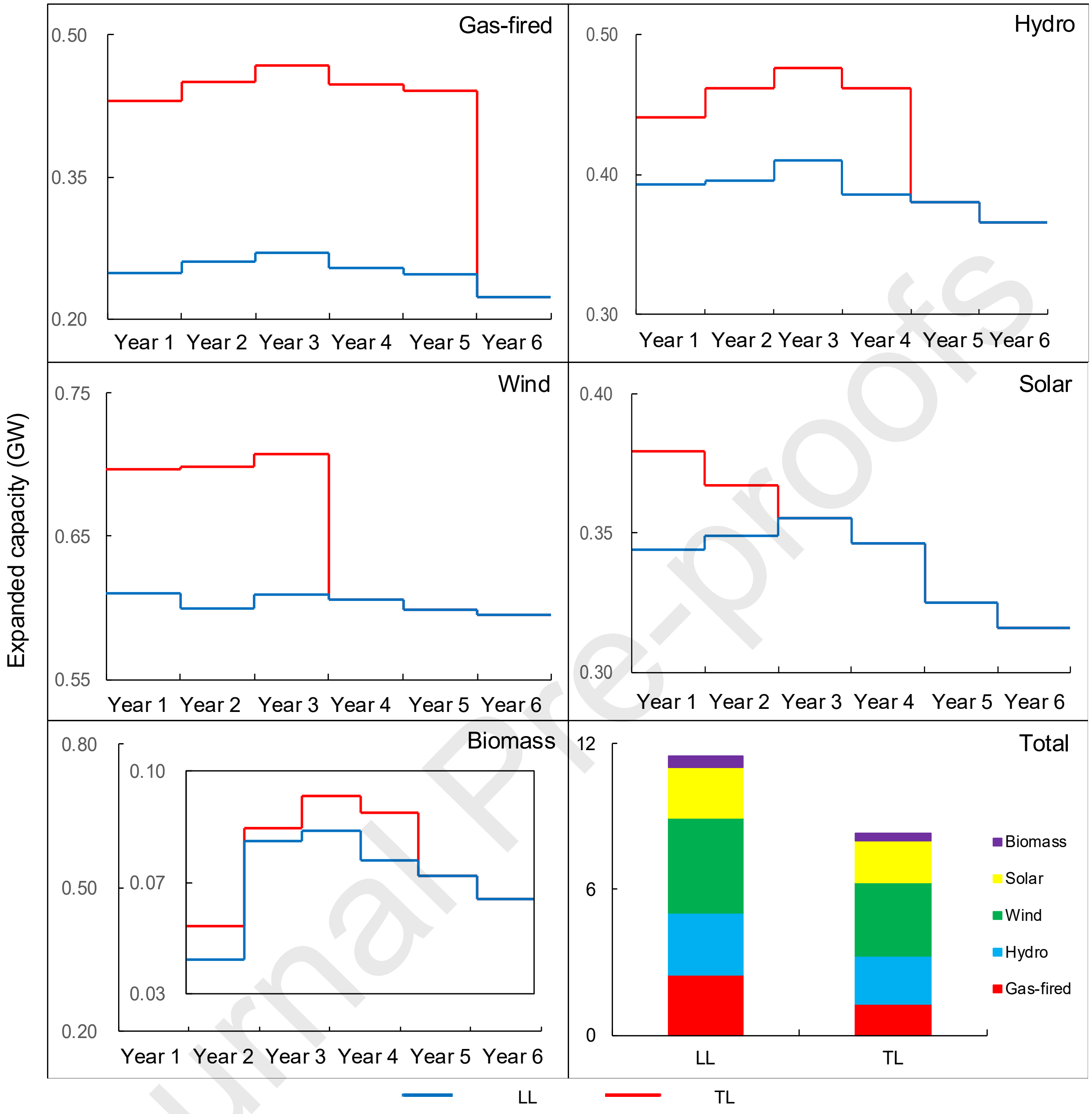


Figure 4. Expanded capacity (GW)

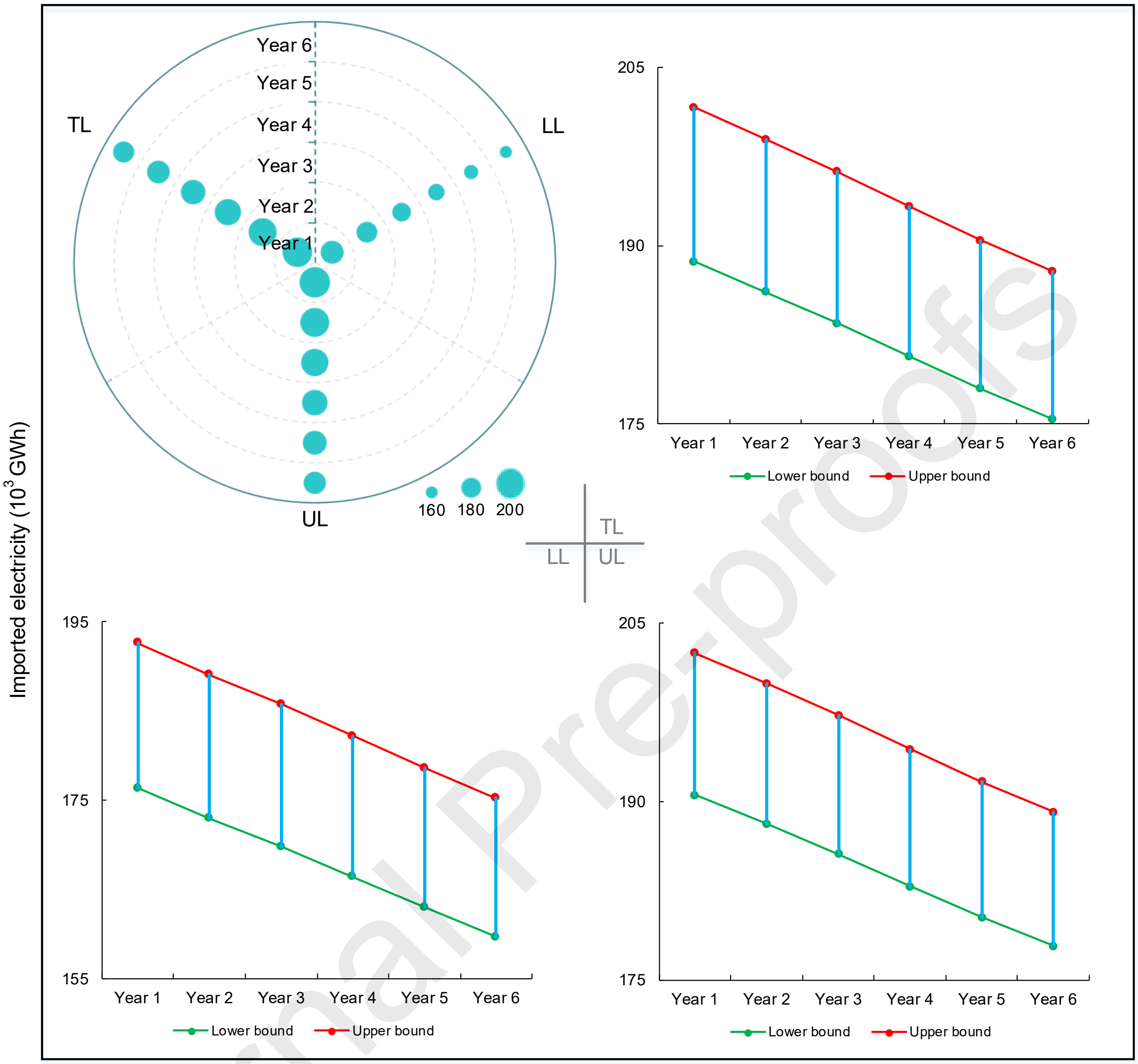


Figure 5. Imported electricity ($10^3$ GWh)

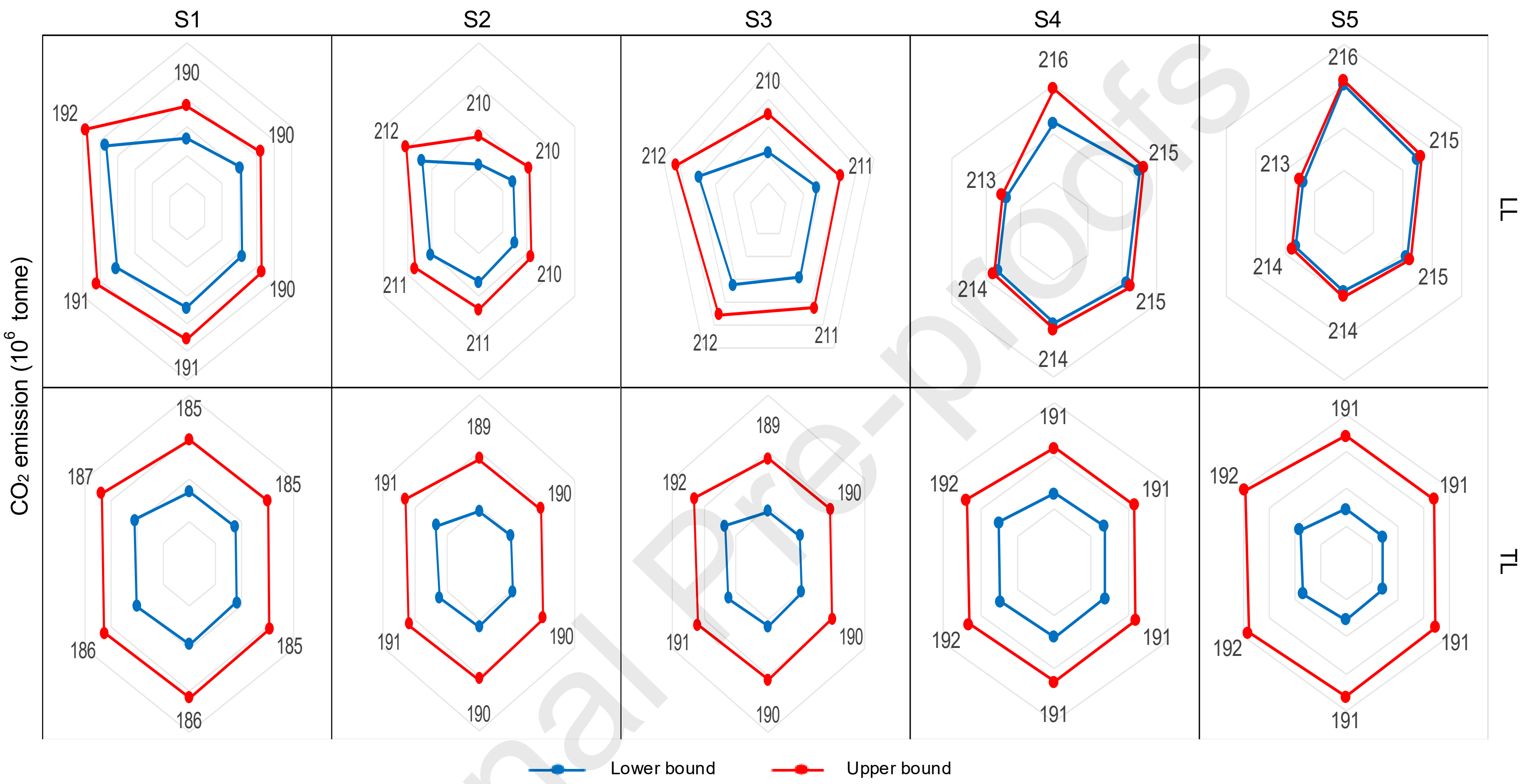


Figure 6. $CO_2$ emission ($10^6$ tonne)

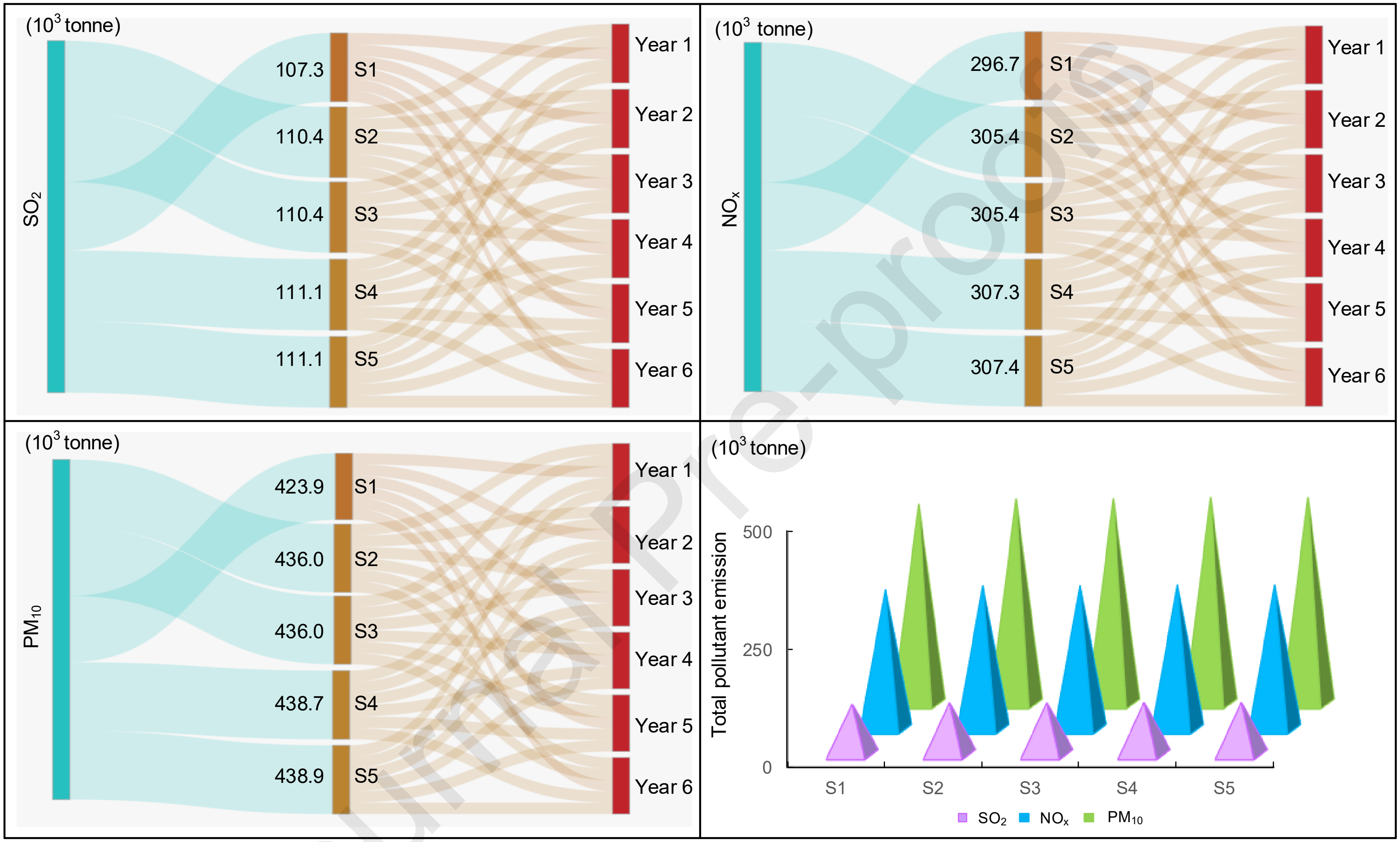


Figure 7. Pollutant emission (10$^3$ tonne)

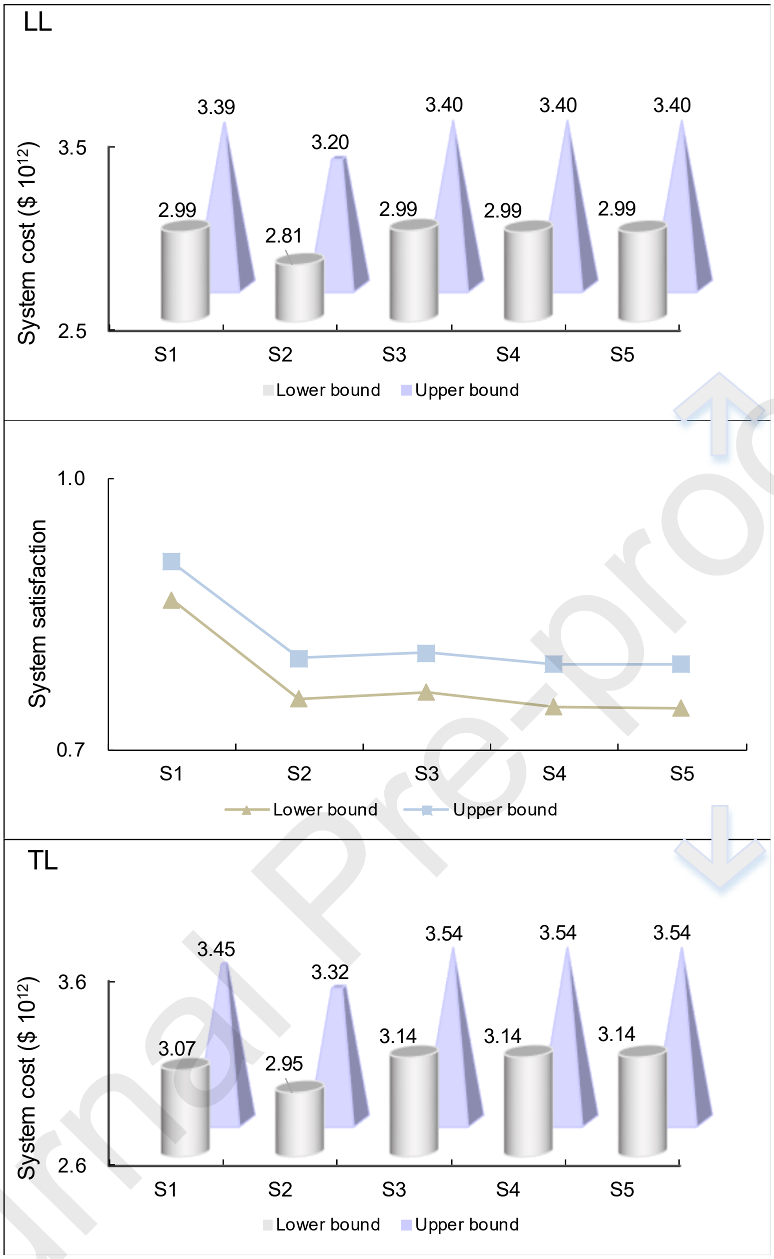


Figure 8. System cost and saticfaction

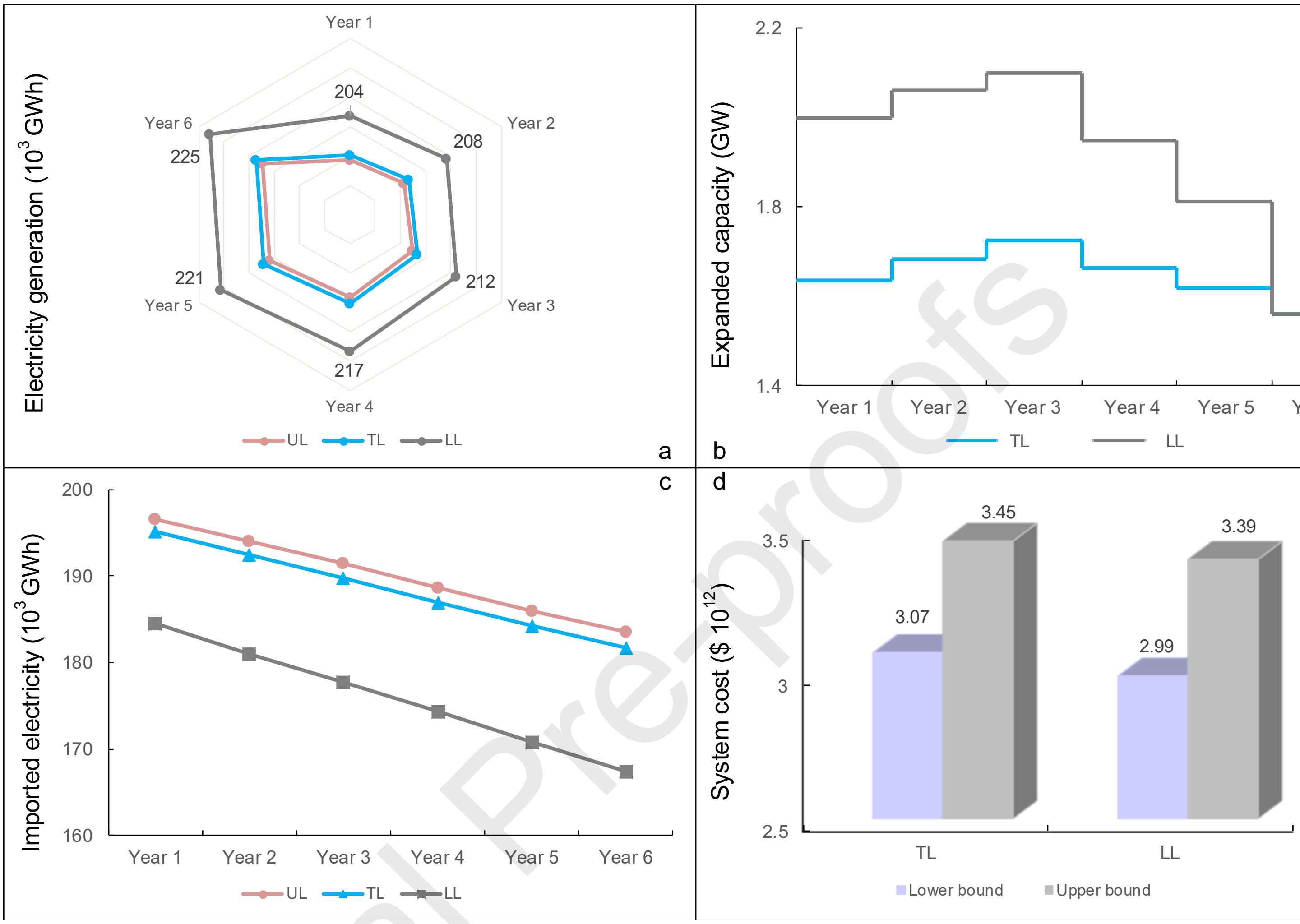


Figure 9. Compared results among UL, TL and LL

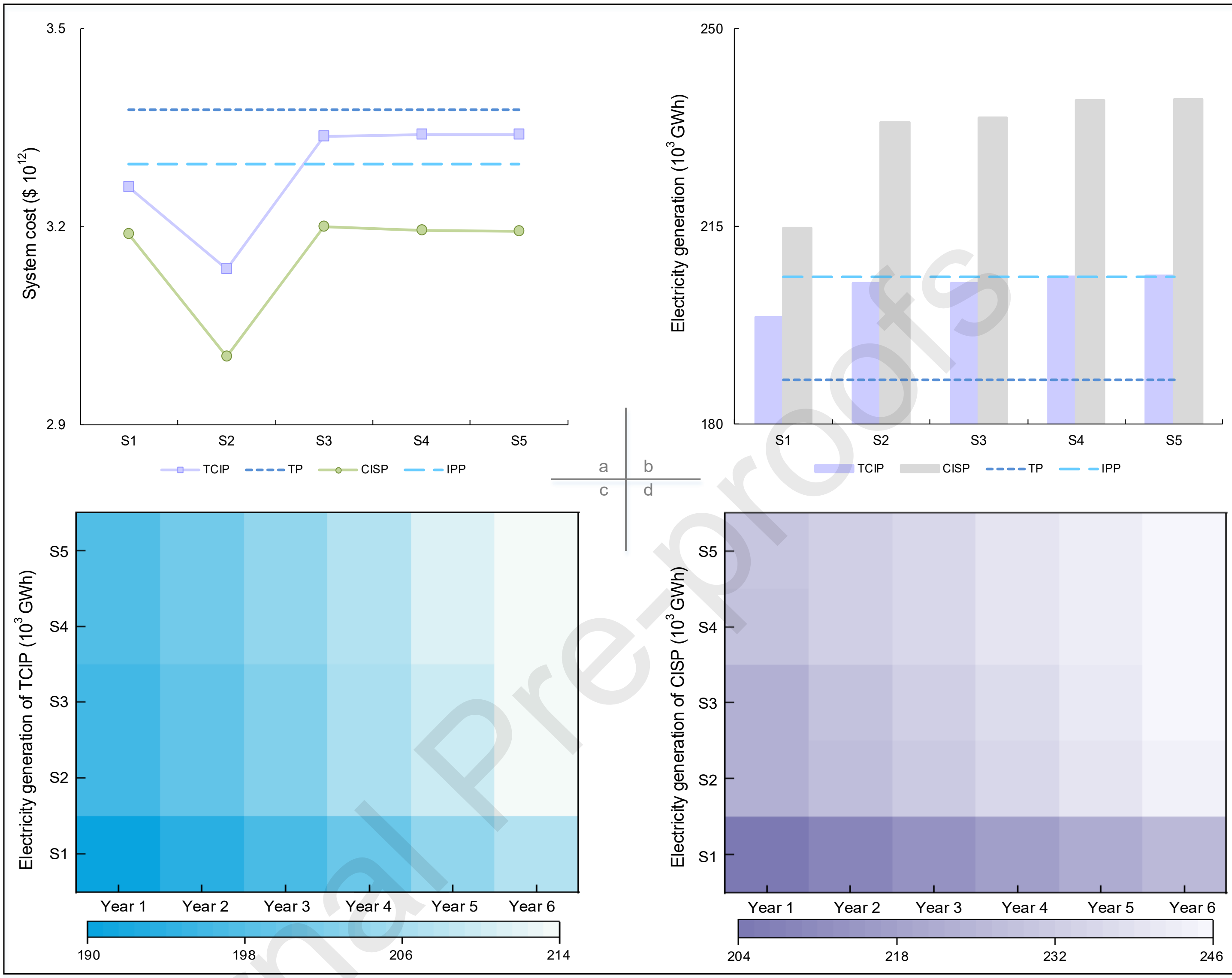
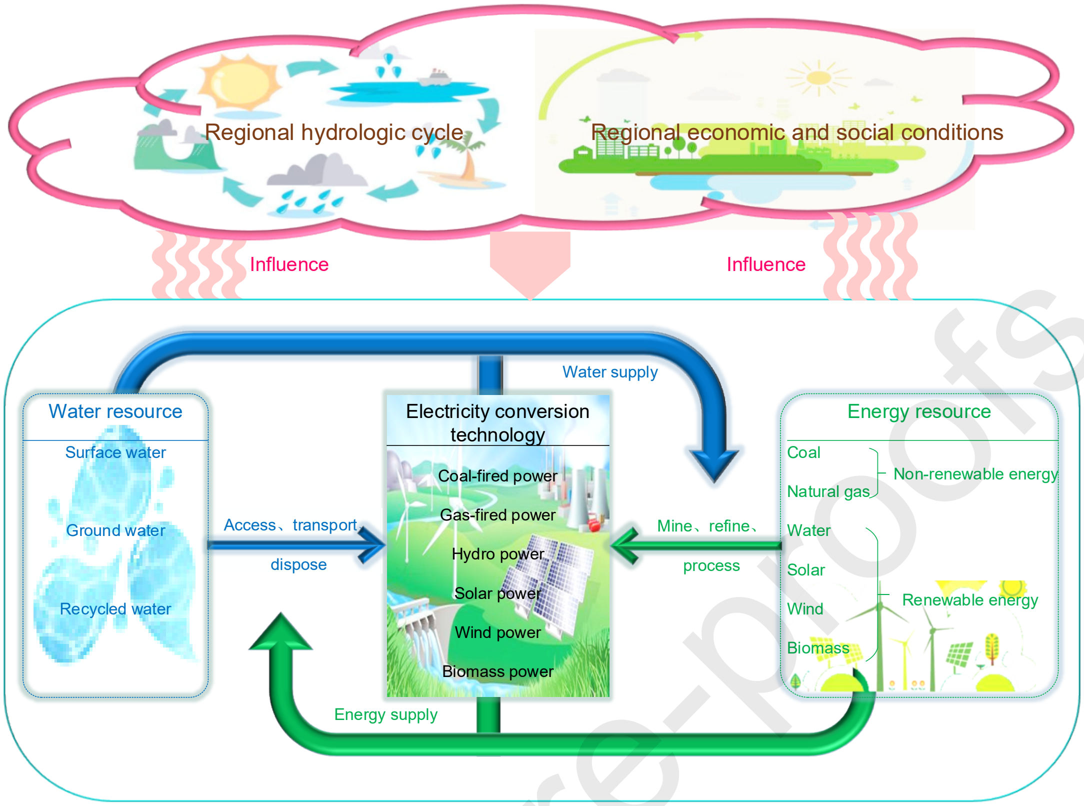


Figure 10. Compared results among TCIP, TP, CISP and IPP



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