Impacts of Water Resources and Carbon Mitigation Policies on Electric Power Systems under Multiple Uncertainties

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Abstract. A bi-level multistage joint-probabilistic left-hand-side chance-constrained programming model is proposed to plan energy-water-carbon nexus systems under multiple uncertainties. The model can address randomness in constraints right- and left- hands as well as handling leader-follower problem in decision-making processes. A variety of scenarios associated with different left-hand side constraint-violation risks as well as a range of levels relate to available water, electricity demand, and carbon mitigation are examined. Results reveal that multiple uncertainties significantly affect the nexus system planning policies (energy supply, electricity generation, imported electricity, water utilization, and carbon emission). Results also disclose that local authorities would vigorously develop wind power and biomass power; available water has the greatest magnitude of the main effect upon the total cost; the interaction among the carbon mitigation and available water have obvious effect on total cost.

1. Introduction
Currently, China faces rapid increases in electricity demand, with an increased amount of 36357 million kWh from 2005 to 2016 [1]. In 2016, the proportion of thermal power (e.g., coal, natural gas, oil), nuclear power, hydropower, wind power and others (e.g., solar, biomass, etc.) generation in national electricity generation were 72.2% (coal-fired power accounted for 65.5%), 3.5%, 19.4%, 3.8%, and 1.1%, respectively (National statistical yearbook, 2018) [1]. It was indicated that electric power system still relied heavily on fossil fuels, while combustion of such fuels consumed large amounts of water at almost every step. For instance, coal-fired power plants used water from mining and washing coal to treating combustion waste as well as cooling turbines [2]. Natural gas-fired power plants used water in drilling, extraction, process, transport, steam make-up, and cooling steps. Water is significant for almost all kinds of energy productions [3]. Electric power sector was the second dominant water consumer after agriculture and the share approaches about 12% of the total water consumption [4].

Previously, several mathematic models were constructed to analyze energy-water-carbon nexus system from different perspectives. Yang et al. (2018) assessed energy consumption, water utilization, and carbon emission of the nexus system in Shanghai and Beijing [5]. Zhang et al. (2018) employed a water-carbon nexus model of hydropower to calculate the water consumption amount per unit GHG mitigation, and maximized GHG mitigation by optimal allocating watershed water resources [6].
Sharifzadeh et al. (2019) developed a stochastic optimization framework with water demand, electricity demand, wind and solar power availability as well as GHG emission mitigation constraints, which gained insights into low carbon electricity generation and their impacts on sewage treatment [7]. Summarily, the above researches mainly aimed at planning energy-water-carbon nexus (EWCN) systems when components were featured with deterministic or single uncertainty characteristics.

Many efforts were made in coping with uncertainties in electric power systems management through inexact mathematical models [8, 9]. Leo and Engell (2018) displayed a multi-stage stochastic programming model that considered uncertain product demands and equipment breakdowns to optimal planning electricity procurement and production schedules [10]. Li et al. (2018) proposed an interval joint-probabilistic two-side chance-constrained programming approach handle the random electricity demands and renewable power generations [11]. Zhang et al. (2016) developed a bi-level decision model to optimize electricity generation, fuel consumption, water utilization; based on different controlling power of different decision makers [12].

This study aims to propose a bi-level multistage joint-probabilistic left-hand-side chance-constrained programming (BMJCP) model for planning energy-water-carbon nexus (EWCN) systems. BMJCP integrates multi-stage stochastic programming (MSP), joint probabilistic left-hand-side chance-constrained programming (JCLP), and bi-level programming (BP) within a general framework, which can handle randomness in constraints right- and left- hands as well as address leader-follower problem in decision-making processes. Then, the BMJCP model is applied to planning EWCN for the City of Qingdao. Solutions for electricity generation, imported electricity, capacity expansion, energy consume, water utilization, pollutants/CO2 emission control, and system cost under multiple scenarios are generated.

2. Methodology
The detailed procedure of solution algorithm for the BMJCP model is summarized as follows:

Step 1: Formulate an BMJCP model.

Step 2: Acquire the model parameters through obtaining their probabilistic distributions (in constraints’ left-hand and/or right-hand sides) and other values.

Step 3. Discrete the probability distributions in constraints’ right-hand sides into a set of discrete values.

Step 3: Identify the joint probabilities and the combination of individual probabilities for the left-hand-side chance constraints.

Step 4: Transform the left-hand-side chance constraints to the approximated linear forms.

Step 5: Reformulate the linear forms of BMJCP model and obtain individual optimal solutions of two single-level model $x_{j^u}, y_{j^u}, f^u$ (upper) as well as $x_{j^l}, y_{j^l}, f^l$ (lower).

Step 6. Based on solutions in Step 5, obtain $f^u_j = (x^u_{j^u}, y^u_{j^u})$, $f^l_j = (x^l_{j^l}, y^l_{j^l})$, and define the fuzzy membership function of the upper-level objective:

$$
\mu_{f^u_j}(f_u) = \begin{cases} 
1, & \text{if } f_u \geq f_u^* \\
\frac{f^{*}_u - f_u}{f^*_u - f_u}, & \text{if } f_u \leq f_u \leq f^*_u \\
0, & \text{if } f_u < f^*_u 
\end{cases}
$$

Step 7: Specify the tolerances of lower-level decision maker’s goal and the membership function for the lower-level objective:
Step 8: A fuzzy max-min operator $\lambda$ is introduced to aggregate an overall satisfaction to satisfy the decision variables $x_{ij}$ of the upper-level decision maker and the decision goals of the bi-level decision makers simultaneously:

$$\text{Max } \lambda$$

subject to:

$$\mu_s(x_{ij}) \geq \lambda$$

(4)

$$\mu_{f_i}(x_{ij}) \geq \lambda$$

(5)

$$\mu_{f_i}(x_{ij}) \geq \lambda$$

(6)

$$0 \leq \lambda \leq 1$$

(7)

$$\sum_{j=1}^{n} x_{ij} \left[ \mu_{rt} + \sigma_{rt} \Phi^{-1}(1-p_r) \right] \leq b_{rt}, \ r = 1, 2, \ldots, R; t = 1, 2, \ldots, T$$

(8)

$$\sum_{j=1}^{n} a_{ij} x_{ij} + \sum_{j=1}^{n} a_{ij} y_{jk} \geq w_{ik},$$

(9)

$$i = 1, 2, \ldots, m_2; t = 1, 2, \ldots, T; k = 1, 2, \ldots, K_j$$

$$\sum_{r=1}^{m} p_r \leq p$$

(10)

$$p_{jtk} = p_{j(t-1)k}, \ j = 1, 2, \ldots, n_2; t = 1, 2, \ldots, T; k = 1, 2, \ldots, K_i$$

(11)

$$x_{ij} \geq 0, \ j = 1, 2, \ldots, n_1; t = 1, 2, \ldots, T$$

(12)

$$y_{jk} \geq 0, \ j = 1, 2, \ldots, n_2; t = 1, 2, \ldots, T; k = 1, 2, \ldots, K_j$$

(13)

Step 9. For given $x_{ij}^u$, it is generally impossible for the lower-level decision maker to find the individual optimal solutions under such strict conditions. The upper-level decision maker allows $x_{ij}$ to fluctuate within a certain range of $[x_{ij} - q_1, x_{ij} + q_2]$, where $q_1$ and $q_2$ are the lower- and upper-bound tolerances specified by the upper-level decision maker, and the most preferred value is $x_{ij}^u$. Constraints (4) to (7) can then be represented as:

$$\frac{x_{ij} - x_{ij}^u + q_1}{q_1} \geq \lambda$$

(14)

$$\frac{x_{ij}^u + q_2 - x_{ij}}{q_2} \geq \lambda$$

(15)

$$\frac{f_u - f_u^*}{f_u - f_u^*} \geq \lambda$$

(16)

$$\frac{f_i^* - f_i}{f_i^* - f_i} \geq \lambda$$

(17)
Step 10. Solve the model and obtain the optimal solutions $x_{jit \text{ opt}}, y_{jitk \text{ opt}}, f_{\text{opt}}$.

### 3. Results and discussion

Coal and natural gas are the main fossil fuel options for Qingdao’s electricity generation. The energy supply solutions for coal and natural gas conversion technologies in the planning horizon are presented in Figure 1. It is clear that coal is dominant in the city's energy supply structure, while its supply amount would decrease with time. For instance, under S12, the highest amounts of coal and natural gas would be $665.52 \times 10^3$ TJ and $296.88 \times 10^3$ TJ in period 1; the highest amounts of coal and natural gas would be $483.97 \times 10^3$ TJ and $362.79 \times 10^3$ TJ in period 4. It is also disclosed that the amounts of coal and natural gas would vary with joint probability levels due to available energy supply, water supply ($p_1$), pollutant emissions control ($p_2$) and CO$_2$ mitigation ($p_3$) (where pollutant emissions control is the main factor).

![Figure 1](image.png)

**Figure 1.** Purchased energy under different scenarios (unit: $10^3$ TJ)

Taking S12 as an example, Figures 2 and 3 show water utilization and carbon emission under different combinations of electricity demand, available water as well as carbon mitigation levels. Figure 2 indicates that coal-fired would be the major water consumer under all levels throughout the planning period because of its high electricity generation and water utilization coefficients. Nevertheless, water utilization of coal-fired power would decrease with time due to the reduced electricity generation. For example, under LD-LS-LM level, the amount would decrease from $309.79 \times 10^6$ m$^3$ (in period 1) to $211.38 \times 10^6$ m$^3$ (in period 4). Water utilization of other conversion technologies would increase with time due to the increased electricity generation. Among them, gas-fired power would consume more than 33.18% of total water over the whole planning horizon. Such phenomenon is caused by its increased generation amount and high unit water demand. It is essential to establish effective mechanisms and financial strategies to encourage energies that with low water requirement as well as low pollutant and CO$_2$ emissions (such as wind power, occupying more than 3.66% of total water) to handle problems of electricity demand increment, and water shortage, and climate change.

Regarding the emissions of CO$_2$, variations are captured with the three raised levels (Figure 3). For
example, compared to LD-HS-LM level (in period 1), the amount would decrease by $1.32 \times 10^6$ ton under LD-LS-LM level; compared to HD-HS-HM level (in period 2), the amount would decrease by $0.13 \times 10^6$ ton under HD-LS-HM level. This is due to the fact that different water availability limits the improvement of local electricity generation and then affecting the emission way. On the other hand, high mitigation level could reduce the CO$_2$ emission. For instance, in period 1, the amount would decrease from $48.00 \times 10^6$ton under MD-MS-LM level to $46.54 \times 10^6$ton under MD-MS-HM level. Such strategy could also promote the local renewable energy development leading to a clean and low risk electricity generation scheme.

![Figure 2. Water utilization](image)

Figure 4 depicts main and combined effects of the three levels on total cost. In the main effects plot, the points are the mean total cost at the various levels of each parameter, with a reference line drawn at the grand mean total cost. This plot reveals that available has the greatest magnitude of the main effect upon the total cost. The total cost would be $2297.12 \times 10^6$, $2289.35 \times 10^6$, and $2282.78 \times 10^6$ under LS, MS, and HS levels, respectively. This is because that higher available water can satisfy the high-water demand of thermal power, leading to less imported electricity and thus a considerable variation in the total cost. Contrarily, carbon emission with a small slope has the smallest contribution to the variability of the total cost, since the carbon emission limit value as well as probability of occurrence under LM an HM levels are relatively close. The full interactions plot matrix reveals that a strong interaction among the carbon mitigation and available water. The effect of available water on total cost would increase when the carbon mitigation level increases.
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Figure 3. CO₂ emission

Figure 4. Main and combined effects
(unit: $ 10^9$

4. Conclusions
In this study, a bi-level multistage joint-probabilistic left-hand-side chance-constrained programming (BMJCP) model is proposed for planning energy-water-carbon nexus (EWCN) systems under multiple uncertainties. The proposed BMJCP can cope with randomness in constraints right- and left-hands as well as address leader-follower problem in decision-making processes. Then, the BMJCP model is applied to planning EWCN for the City of Qingdao under multiple scenarios of carbon emission-mitigation policies, water-utilization strategies and electricity-demand levels. Results discovered that: i) λ (satisfactory degree) and system cost would increase with the raised joint probability levels; ii) coal and natural gas would vary with joint probability levels due to available energy supply, water supply (p1), pollutant emissions control (p2) and CO₂ mitigation (p3); iii) electricity generation is sensitive to the constraint-violation risk, electricity demand, available water, and carbon mitigation; iv) imported electricity would decrease with the raised joint probability values; v) electricity generation from clean energy would increase, in which natural gas and wind would account for a large proportion. Results can help local authorities to adjust existing policies related to energy-water nexus systems, and achieve the goal of using energy in a sustainable way.

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