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Planning energy-water nexus system under multiple uncertainties – A case study of Hebei province

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HIGHLIGHTS

- An interval-fuzzy chance-constrained programming method is developed.
- It can address uncertainties expressed as interval values and fuzzy random variables.
- Energy-water nexus system optimization model is formulated for Hebei, China.
- Tradeoffs among system cost, electricity demand and water resources are analyzed.
- The proportion of coal-fired power would reduce by about 12.09% in 2023.

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ABSTRACT

Energy and water are inextricably linked. The shrinking water availabilities, increasing energy demand, and severe resources shortage pose great challenges for socioeconomic sustainable development. In this study, an interval-fuzzy chance-constrained programming method that is capable of addressing uncertainties expressed as interval values, fuzzy sets and fuzzy-probability distributions existed in the energy-water nexus system is developed. Then, the developed method is applied to a real case of Hebei province (in northern China) that heavily relies on fossil fuels such as coal and oil as sources of energy. A variety of scenarios associated with different water availabilities and multiple uncertainties are examined. Results reveal that both water availabilities and uncertainties have significant effects on the energy-water nexus system planning strategies. Compared to the scenario with high water-availability, the energy-water nexus system would save 10.9% of water under low water availability; however, the imported electricity would increase 8.2% to offset the local power-generation shortage. Results also disclose that the study system would gradually transit to renewable energies and the proportion of coal-fired power would reduce by 12.09% at the end of planning horizon. These findings can provide useful information for the other regions to achieve adjustment of the conflict among economic objective, electricity demand, and water shortage.

1. Introduction

1.1. Motivation

Energy and water, two widely-recognized critical resources for improving human livelihood and building harmonious society, gain international attention as demand for both resources mount [1]. It is estimated that by 2030, the shortage of global water supply will be 40% and nearly half of the world's population will be living in areas of high water stress affecting energy security [2]. Besides, global energy demand will grow 36% by 2030 compared to 2010 which will put additional pressure on already limited water resources. Furthermore, water shortage could challenge the stability of energy system and the viability of capacity expansion, and thus resulting additional costs [3]. To alleviate the challenges posed by the nexus, the World Bank launched a new global initiative entitled "Quantifying the Tradeoffs of the Water and Energy Nexus" and started an initiative called "Thirsty Energy" to assist developing countries assess and quantify the tradeoffs among

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Nomenclature

α_t	transmission loss in period t (%)
$f^{\pm}$	lower bound and upper bound of the system cost ($\$10^9$)
j	electricity conversion technology, with j = 1 for coal-fired power, j = 2 for gas-fired power, j = 3 for hydro power, j = 4 for solar power, j = 5 for wind power, j = 6 for biomass power, j = 7 for imported electricity
t	planning period, t = 1, 2, …, 5
q	expansion option, q = 1, 2, 3
m	types of air pollutants and carbon dioxide, with m = 1 for SO_2, m = 2 for NOx, m = 3 for PM_{10} and m = 4 for CO_2
CCW_t	cost for cooling water in period t ($\$10^6/m^3$)
$CEEF_{jqt}$	variable cost for expanding electricity-conversion technology j in period t ($\$10^6$/GW)
CET_t	cost for electricity transmission in period t ($\$10^6$/GWh)
CHW_t	cost for boiler water in period t ($\$10^6/m^3$)
CI_t	cost for imported electricity ($\$10^6$/GWh)
COE_{jt}	electric operating cost of conversion technology type j in period t ($\$10^6$/PJ)
CPR_{mt}	cost for emission of pollution type m in period t ($\$10^6$/103 tonne)
CPT_{jmt}	environmental facilities cost for pollution type m in period t ($\$10^6$/103 tonne)
CQE_{jt}	cost for coal and natural gas ($\$10^6$/PJ)
CSW_t	cost for desulfurization water in period t ($\$10^6/m^3$)
CW_{jt}	cost for other type water in period t ($\$10^6/m^3$)
EEF_{jt}	fixed cost for expanding electricity-conversion technology j in period t ($\$10^6$)
	consumption rate of energy resource in electricity-conversion technology j (PJ/GWh)
ERR_{jmt}	emission reduction rate of pollution type m in period t (%)
L_{jt}	service time of electricity-conversion technology j in period t (hour)
PRR_{jmt}	emission efficiency of pollution type m in period t (10^3 tonne/GWh)
$TPRR_{mt}$	allowed amount of pollution type m in period t (10^3 tonne)
$TQEN_t$	total electricity demand in period t (GWh)
TQW_t	amount of available water resource in period t (m^3)
QCW_{jt}	cooling water for electricity-conversion technology j in period t (m^3/PJ)
QE_{jt}	amount of available energy resource in period t (PJ)
QEC_{jt+1}	installed capacity of electricity-conversion technology j in period $t + 1$ (GW)
QEE_{jqt}	expanded capacity of electricity-conversion technology j under expansion option q in period t (GW)
QEG_{jt}	amount of electricity generation in electricity-conversion technology j (GWh)
QEI_t	amount of imported electricity in period t (GWh)
QHW_{jt}	boiler water for electricity-conversion technology j in period t (m^3/PJ)
QSW_{jt}	desulfurization water for electricity-conversion technology j in period t (m^3/PJ)
QW_{jt}	other type water for electricity-conversion technology j in period t (m^3/PJ)
Y_{jqt}	0–1 variables for identifying whether or not electricity generation facility j need to be expanded in period t

economic, environmental and social in energy production under water constraints [4].

China, as the largest developing country, accounts for 21% of the global energy consumption, but only occupies 6% of the world's freshwater resources [5,6]. With the rapid population growth and speedy economic development, China is facing the increasingly strained conflicts between supply capacities and final demands of these interlinked resources. The national electricity demand will increase at a rate range of 4.2–5.0% from 2016 to 2020, in which more than 57% of the total power supply still relies on fossil fuels [7]. However, the coal life cycle is very water intensive, from coal mining and washing to cooling of power plants [8,9]. Water for energy-generation process is huge, reaching 17% of the total water consumption. The Chinese government, recognizing the complex nexus between energy and water, added "water-for-coal" plan to the "3 Red Lines" water policies in 2013 in which effectively managing the limited water resources to answer challenges of increasing energy demand [10].

In the real-world problems, the utilization of energy and water resources is significantly affected by specific limitations associated with individual conditions and the constraints imposed by their interactions [11,12]. In detail, water is needed for fuel mining, biomass crops, hydropower generation, steam generation, cooling and infrastructure manufacture [13]. Meanwhile, energy (mainly in the form of electricity) is required for the supply, treatment, desalination and distribution of water resources [14]. It is clear that the energy and water resources are inextricably linked and that occur in three categories (i.e., production, transportation and consumption) [15]. For example, electricity is consumed to treat wastewater, and the obtained recycled water can then be used for cooling in thermal power plants. This intertwined relationship is commonly called as the energy-water nexus which plays an important role in resolving real dilemmas of city in terms of technical and policy aspects [16]. Generally, population growth, socioeconomic development, energy-demand increase, and climate change are exerting ever-increasing pressure on energy-water nexus (EWN) system, forcing researchers to propose robust methods and managers to make solid decisions regarding water use for energy system with a more sustainable economic and environmental manner [17].

1.2. Literature review

Previously, many research works were conducted for analyzing energy-water nexus (EWN) system from different perspectives. Lubega and Farid [18] presented a quantitative integrated model based on energy-water nexus which was capable of calculating the flows of matter and energy across and between the system boundaries of the electricity, water, and wastewater systems. Chen and Chen [19] introduced input-output analysis to synthesize the interwoven connections between energy consumption and water use, in which the intensities and structure of the study city's energy-water nexus networks were collectively assessed and results found that direct and embodied energy/water flows were distinct in terms of the configuration of sectorial consumption. Valek et al. [20] analyzed the water system related energy use and carbon emissions of Mexico and focused on water supply system and the wastewater treatment system. Huang et al. [21] developed a China model to integrate energy system with water resources to predict water demand in power sector and to assess the impacts of carbon and water constraints on power generation structure out to the year 2050. Khan et al. [22] analyzed Spain energy-water system across spatial and temporal scales to reduce the system cost and improve the resources efficiency. Tsai et al. [23] proposed an integrated simulation modeling system for renewable energies and water resources to obtain strategies of operation alleviating the impact of intermittent characteristics of each resource. Generally, the above research efforts mainly focused on managing EWN when system components and parameters were deterministic.

In the practical EWN planning problems, many uncertainties exist in various energy- and water- related activities, which are caused by the