Renewable and Sustainable Energy Reviews 99 (2019) 125–137

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Integrated risk analysis of water-energy nexus systems based on systems dynamics, orthogonal design and copula analysis

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ARTICLE INFO

Keywords:
Risk analysis
Water-energy nexus
System dynamics
Orthogonal design
Copula analysis

ABSTRACT

Within specific cities or regions, water and energy are intimately and highly interwoven, forming water-energy nexus (WEN) systems. Such a nexus system is complicated, leading to the generation of coupled risks of water and energy resources. In this research, an integrated approach of systems dynamics, orthogonal design and copula analysis (IA-SOC) was developed for supporting risk analysis of WEN systems. Innovations of this approach includes: 1) the development of a method through coupling system dynamics and orthogonal design, and 2) the combination of Copula analysis for supporting interactive risk assessment of both water and energy resources. The proposed approach was applied in Jing-Jin-Ji (J-J-J) region to deal with risk analysis of WEN and promote coordinated development. The results showed that: 1) the established system dynamics models can be employed to predict the water and energy demands; 2) the orthogonal table $L_{27}(3^{13})$ can be adopted to obtain the representative scenario combinations, which could be introduced into system dynamic models to obtain the water and energy demands over the planning period; 3) it was appropriate to employ Lognormal distribution to establish the marginal distribution function of water and energy resources, meanwhile the Bivariate Frank Copula function was adopted to construct the joint distribution function of WEN to quantify the inherent relationship between water and energy resources; 4) the demands for water and energy resources in J-J-J region over the planning period were [252.06, 290.7] billion m^3 and [433.67, 477.02] million tons of standard coal equivalent (S.C.E.), respectively. Correspondingly, the shortage risks of water and energy resources were [0.938, 0.981] and [0.835, 0.936]; and 5) different scenario combinations were set to identify the controlled amount of water and energy demands. The results could provide reasonable policy recommendations on the risk analysis of water and energy resources to promote regional coordinated development.

1. Introduction

Water and energy are fundamental and essential resources for social development and economic growth [1,2]. Along with population explosion and urbanization, demands for water and energy are continuously rising, making many cities face cascades of problems such as water and energy shortage. According to relevant studies, global demands for water and energy resources are supposed to increase by 55% and 80% in 2050 [3]. This is particularly obvious in China. For example, water consumption in the Jing-Jin-Ji (J-J-J) region of China has increased by 3.9% from 2005 to 2014 [4–6]. At the same time, energy consumption in this region over the same period has grown from 294.43 to 442.97 million tons of standard coal equivalent (S.C.E.). In the region, water and energy consumptions are interacting with each other, leading to the formation of a water and energy nexus (WEN) system. For example, a large amount of water resource is required for energy supply, such as power generation and coal mining. At the same time, certain amount of energy resource is needed for water extraction, storage, transmission and treatment [7]. This has caused many practical problems and management challenges to local decision makers. Moreover, multiple levels of interactions are existing in WEN systems of many cities and regions. A series of studies show that water and energy issues are inextricably linked and intertwined. In 2015, the total water consumption of J-J-J region was 251.07 billion m^3. Correspondingly, the total consumption of energy resource was 443.26 million tons of S.C.E. Obviously, such a synergy increase of energy and water consumptions would correspondingly require a synergic management of water and energy to minimize the associated coupled shortage risks of

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https://doi.org/10.1016/j.rser.2018.10.001
Received 12 November 2017; Received in revised form 12 August 2018; Accepted 4 October 2018

water and energy. In addition to the correlations between energy and water consumptions, multiple level of interwoven interactions are existing in many components, factors, and processes of both water and energy subsystems, leading to a variety of complexities in quantifying coupled risks of water and energy shortage and providing effective tools in managing water and energy. Process of water and energy production, transmission and consumption are closely intertwined and interdependent [8,9]. It is thus necessary to quantify the relationship between water and energy resources, and identify their potential synergy risks. Therefore, identify and evaluate potential coupled risks of water and energy shortage is desired in many regions such as J-J-J region that is the priority for sustainable development in China.

More recently, with the increase of population and the shortage of water and energy resources, WEN has become the research focus all over the world. Obviously, research for WEN is complicated. On the one hand, an individual WEN system consists of water and energy subsystems. Meanwhile, these two subsystems contain multiple layers and components. There exist intricate and complex interactions in the two subsystems and the related internal components. Any changes in one of the subsystems and the related components can lead to positive or negative impacts on the other subsystem and the corresponding components. On the other hand, water and energy resources interact with each other, which lead to synergy of potential shortage risks in WEN systems. Previously, there are many studies on WEN systems. The adopted methods mainly include life cycle assessment [10,11], input-output analysis [12,13], virtual water accounting [14,15], national account [16,17] and econometrics [18,19]. For example, Gu et al. [13] analyzed water energy nexus in major Chinese industries through using a series of input output tables. Their results indicated that water-saving effects can be identified through the adoption of certain energy-saving policies. Zhou et al. [18] employed a multi-sectoral dynamic computable general equilibrium (CGE) model to analyze potential impacts of energy policies on water resources consumptions. As one of effective econometric methods, Copula analysis is considered as a favorable method to construct the joint probability distribution and describe the interdependency between random events and variables [20]. It can connect two or more random variables and events flexibly for establishing the joint distribution and reflect the relationship among the variables and events. It has been widely applied in many areas such as insurance, financial, and hydrological studies [21–23]. Kong et al. [24] proposed Gumbel Copula for simulating two adjacent monthly stream flows. The simulated results indicated the performances of Gumbel Copula method and the associated deviations. Li et al. [25] constructed the multidimensional joint probability functions of flood peaks, volume and duration through the adoption of entropy Copula, which can effectively reflect probability distributions of flooding events.

At the same time, a few researchers focused on risks associated with resources such as water and energy [26–29]. Generally, the purpose of risk analysis is to pre-assess the undertaken risk of the system for achieving any desired goal, which can help decision makers improve the follow-up measures in advance to ensure the safety and reliability of decision-making processes [30]. It has been extensively used in many fields in the recent half a century. Kong et al. [31] developed a factorial-based two-stage programming with fuzzy random value-at-risk approach to reveal the impacts of uncertain parameters on water resources management strategies and the corresponding risks. A multiple water users chance-constrained dynamic programming model was proposed by Li et al. [32] to explore water resources allocation and the associated water shortage risks in Beijing, China. Asefa et al. [33] established a risk assessment model to evaluate reliability, vulnerability and stability of water resources systems under varying climatic conditions. Gatzert et al. [34] presented the current risks and risk management solutions of existing renewable energy projects and identified critical gaps in risk evolution. Liu et al. [35] proposed a fault tree analysis and catastrophe model to implement a complete and comprehensive risk management on rural energy industry of Sichuan Province, China.

The previous studies have the following limitations: a) most of these studies focused individually on management of water and energy resources, and hardly deal with coupled risks of water and energy shortage, b) they seldom addressed interactive changes of multiple key parameters that could significantly affect WEN systems and the associated subsystems, and c) none of these studies attempted to handle interactions of the coupled risks. To remedy such limitations, a comprehensive approach through the development of a new method will be proposed in this research. An integrated approach of system dynamics, orthogonal design and copula analysis (IA-SOC) will be proposed in this research. Innovations of this integrated approach includes: 1) advancement of a method coupling system dynamics and orthogonal design. The system dynamics model will be proposed to predict the water and energy demands. Then the representative factors will be selected by the orthogonal experimental design method, identifying representative scenario combinations and introducing them into the system dynamics model of water and energy demands for prediction; and 2) combination of the copula function with risk analysis. The copula function can be employed to quantify the interaction of water and energy resources. Then the controlled amount of water and energy demands can be obtained through incorporating the copula function into risk analysis of WENs and developing a variety of scenario combinations, which consist of synergy risks of WENs, as well as individual shortage risk of water and energy. Thus, the objective of this research is to develop an integrated approach of system dynamics, orthogonal design and copula analysis for supporting risk analysis of water-energy nexus. This approach can help identify and quantify water–energy nexus, and assess their synergy risks of water and energy shortage. It will then be applied in J-J-J region to explore internal relationships between water and energy resources for supporting quantification of water-energy nexus, analysis of synergy WEN risks, and promoting coordinated development of J-J-J region.

2. Methodology

2.1. A systematic framework for coupled risk analysis

The integrated approach for coupled risk analysis of water and energy nexus (WEN) systems consists of four components: 1) a system dynamics module for projecting demands for water (including industrial, agricultural, domestic and ecological sectors) and energy (including primary industry, secondary industry, tertiary industry and domestic energy) systems, 2) an orthogonal design module for investigating multiple groups of sensitive parameters, 3) a copula analysis module for analyzing coupled risks of water and energy shortage, and 4) a module for supporting risk analysis. Firstly, a system dynamics method is employed to predict demands for water and energy resources. It is a widely utilized approach for understanding the nonlinear behaviors of the complex nexus systems over certain periods. At the same time, to reflect corresponding dynamics of system outputs under changes of relevant parameters, methods of scenario analysis have been employed to be integrated into system dynamics. However, scenarios design of traditional system dynamics methods cannot avoid the limitations in relevant parameters or irrationality of excessive combinations of scenarios, which can hardly reflect the overall situation and interactions of complex systems such as population, economic, and environment. Comparatively, orthogonal design method can be adopted for arranging test and solving the multi-parameters problems of water and energy demand subsystems. It is an appropriate way to analyze the interactions of multi-factors and multi-levels. Thus, the overall situation of a complex system can be grasped through selecting representative combinations from full factorial experiments. The developed approach can thus couple system dynamics with orthogonal design for helping reflect effects of multiple interactive parameters under the synthetical changes of complex systems. Thirdly, copula