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Embodiment of virtual water of power generation in the electric power system in China

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HIGHLIGHTS

- A virtual scarce water method is proposed to investigate the electricity power systems.
- Virtual scarce water is transferred via power transmission system.
- Virtual water flows from inland areas to coastal areas in the power system of China.

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ABSTRACT

Increasing severe water deficiency has led to an urgent need for better water resource management, especially in China. Electric power systems have been recognized as large water consumers; therefore, comprehensive analysis of their water use is needed. This study aims to analyze the flux and direction of virtual water and virtual scarce water within power system based on transmission–consumption water intensity (TCWI). A case study is then conducted to investigate China's electric power system. The results show that including the water stress index (WSI) and virtual scarce flow concept largely influences the analysis of interregional virtual water flows. Regardless the WSIs, there are four regions exporting virtual water (northeast, north, northwest and central) and two regions exporting virtual scarce water (east and south). While considering the virtual scarce water, the central region becomes a big exporter with 144.12 GL of virtual scarce water outflow. In addition, the virtual water and virtual scarce water flux among these six regions reaches 726 GL and 163 GL, respectively. The electric transmission system transfers virtual scarce water from inland areas to coastal areas, which is roughly the opposite of the distribution of China's water resources. The virtual water analysis incorporating the water scarcity not only largely increases the effectiveness of the results, but also provides more valuable and accurate information for water-efficient management and planning in electric power system.

1. Introduction

Water use grows rapidly with economic development, resulting in increasing water shortages. This is especially true for China, where the annual availability of renewable water resources per capita is only 25% of the world average [1]. Effective water resource management is essential to ease China's pressure on water resources [2].

Electric power systems are considered a major source of air pollutants, but their impact on water resources is often neglected [3]. With the biggest electric power system in the world, China's electric power industry has consumed a great deal of water. Indeed, 79% of water withdrawal and 47% of water consumption of energy production in China in 2007 were associated with the electricity generation [4]. Furthermore, expected substantial increases in power generation capacity [5] will exacerbate the current water shortage. Thus, in-depth water use understanding within electric power systems is essential to improve water resource management in China.

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Water use associated with different electricity generating technologies has received wide attention, particularly for the cooling systems of conventional plants that utilize heat to generate electricity [6–8]. Detailed descriptions and quantitative analyses of water use in various cooling systems show that water use varies widely among different systems [3,9]. Meanwhile, upstream water use plays a significant role in renewable plants without cooling systems, such as wind facilities [10]. Li et al. estimated the life cycle of wind power in China and found that indirect water use greatly affects the results of the water resource analysis [11]. Besides, water use for hydropower generation is very complicated since reservoirs usually have more than one function [12], such as water storage for agriculture or domestic use. Generally, only water evaporation is considered as the operational water consumption of hydropower plants, since it is hard to disaggregate the end uses of hydropower dam water into agriculture or domestic use [13]. In addition, local climatic differences have certain influences on water evaporation, which should be considered as a significant factor when water use associated with hydropower is investigated [14]. All these studies above focus on the power generation, while the power transmission is less investigated, which can be dealt with through the term 'virtual water'.

To achieve a more comprehensive water use analysis, Allan first proposed the term 'virtual water' in 1994, defining it as the water used to produce food crops that are traded internationally [15]. The concept was then further developed to include the volume of water required to produce a commodity or service [16,17]. Since then virtual water has been widely applied to water resource accounting on various scales, including cities [18–20], countries [21–23] and world [24,25]. All these analyses showed that virtual water accounting can bring comprehensive and accurate insights into water management issues. Recently, virtual water was also used to investigate the water issues within the specific engineering and technological systems or sectors, such as wastewater treatment system [26], building's engineering system [27] and service sector [28].

Virtual water transfer concurrent with trade has shown a huge impact on water resource accounting [29–32]. Global virtual water trade network based on IO framework indicates that the number of trade connections and volume of virtual water trade have more than doubled in the past twenty years [33,34]. Incorporating water scarcity as a potential impact factor, Lenzen et al. [35] further provided new insight into the global virtual water trade. At national scale, the virtual water flows within the trade among UK and other three world regions have been investigated in [36,37]. The results of these estimates show that more than half of the UK's consumption water footprint is from other countries through international trade, reflecting the importance of virtual water flows among different countries. Feng et al. [38] assessed virtual water flows in the Yellow River Basin (YRB) in China from a consumption perspective and found that activities outside the basin also influenced water resource use in the YRB. The provincial virtual water transfer in China was also evaluated by the multi-region input–output (MRIO) model, demonstrating that virtual water flows from northern areas to southern areas, and from underdeveloped areas to developed areas [39,40].

Similarly, virtual water can be used to analyze the water transfer associated with electric power systems, which reflects the life cycle assessment of goods and services for power generation in terms of water use [41]. Recently, life cycle water consumption by different types of power generation in China was analyzed by Feng et al. [42], where a hybrid method integrating the process-based life cycle analysis and the input–output life cycle analysis was used to calculate both the direct and indirect water consumption. Zhang et al. [4] used MRIO to analyze the regional life cycle water use associated with electric power industry. One benefit is that the impact of interregional electric power transmission is considered.

This study was conducted to investigate the water issue of electric power systems, particular the electric transmission systems, with a new perspective on electricity flows rather than economic flows. Transmission–consumption water intensity (TCWI) in the electric power system was defined to transform electricity flows into virtual water flows. The electric network theory was then used to describe the migration of virtual scarce water within the electric power systems in the matrix form. Besides, the water stress index (WSI) concept was incorporated to calculate the virtual scarce water flows, thereby bringing a more comprehensive virtual water analysis. Finally, a case study to quantify virtual water and virtual scarce water flows concurrent with electricity flows in China's electric power system was conducted.

2. Method and data

An example of an electric power system with five regions and electricity flows is shown in Fig. 1. A region can be considered a component containing four branches and one node (Fig. 2a). There are local branches and interregional branches. The former contains a generator branch, which represents the local power plants, as well as a load branch that represents the local power consumers. The latter contains branches that connect other regions, which can be divided into line-in and line-out branches. Since water is required to produce electricity, the virtual water will move with electricity in the same direction. Consequently, the whole electric power system can be considered as a topological network composed of nodes and branches (Fig. 2b).

It should be noted that in the analysis regions could be cities, provinces or countries, with more accurate estimations being obtained for smaller regions.

2.1. Method

For convenience, the description of the method focuses on one region marked by j, the node in it is also marked by j. It is assumed that there are K generators and P loads in region j, and M lines are connected with node j.

2.1.1. Generator branch

The electricity flux of the generator branch in region j can be calculated as the total amount of power generation flows injected into node j,

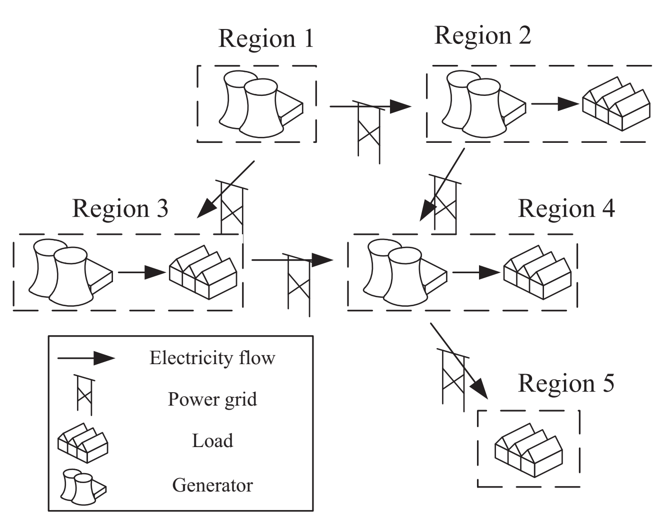

Fig. 1. Schematic diagram of electric power system.