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Connecting water and energy: Assessing the impacts of carbon and water constraints on China's power sector

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HIGHLIGHTS

- An integrated assessment framework was developed by combining China TIMES model with water module.
- CO_2 mitigation target can help reduce both carbon emission and water withdrawal in power sector.
- Water cost has significant impact on water withdrawal in power sector.
- When both CO_2 and water constraints are considered, renewable technologies will be more prevalent.

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ABSTRACT

Energy, water and carbon are inextricably linked. The limited endowments, uneven temporal and spatial distribution of energy and water resources pose great challenges to China's sustainable development. In this paper, a bottom-up model (China TIMES model) is developed to integrate China's energy system with water resources, to project water demand in power sector and to assess the impacts of China's *Intended Nationally Determined Contributions* (INDC) and water constraints on power generation portfolio out to the year 2050. The modelling results show that: (1) under reference scenario, electricity generation will increase from 4518 TW h in 2010 to 13,270 TW h in 2050, with CO_2 emission from 3.1 Gt to 6.1 Gt and water withdrawal from 59 Gm^3 to 104 Gm^3; (2) CO_2 mitigation target can help reduce water withdrawal in power sector by promoting the expansion of renewable technologies; (3) by affecting the cooling mixture, water cost has significant impact on water withdrawal in power sector; (4) when both CO_2 and water constraints are considered, renewable technologies will be more prevalent.

1. Introduction

Energy and water resources are two main bases for human life and social development. China is currently facing a series of energy and water issues, such as limited energy and water resource endowments, uneven temporal and spatial distribution, low utilization efficiency, energy-related carbon emission and climate change. The energy and water issues have restricted the improvement of living standard and the development of social economy. In light of China has the largest population and during the crucial stage of industrialization and urbanization, the need of more reasonable and cost-effective utilization of energy and water resources is urgent and vital, than many other developed countries.

In recent years, to ease the pressures on energy and water issues, Chinese government has set a list of binding targets on energy and water utilization, and proposed a series of "energy saving and emission reductions" and "water saving and pollution control" measures [1,2]. In July, 2015, China government restated its post-2020 climate action commitment, Intended Nationally Determined Contributions (INDC) to peak its emissions around 2030 by reducing CO_2 emissions per unit of GDP by 60–65 percent below 2005 levels and increasing its share of non-fossil fuels in primary energy consumption to around 20 percent by the same year.

Energy and water are inextricably linked. On one hand, water is used in the whole chain of fuel production and power generation, such as coal mining and washing, gas and oil extraction, coal-to-liquids, coal-to-gas and power generation. On the other hand, energy is also used in the whole chain of water exploitation and consumption, such as water exploitation, water desalination and waste water treatment [3–5]. The significant connection between energy and water has called for an integrated analysis of energy and water for the rational development and utilization of China's energy and water resources.

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Up to now, a number of studies have been carried out to evaluate the connection of energy and water resources in fuel production and power generation. An extensive literature review of energy and water nexus can be found in Refs. [6–10]. One interesting research in this regard was done based on the integrated CLEW model (*Climate, Land, Energy, and Water*) at country level. It integrated the WEAP (Water Evaluation and Planning System) model for water, LEAP (*Long-range Energy Alternative Planning*) model for energy, and the AEZ (*Argo-Ecological Zoning*) model for land-use [6]. Another energy–water analysis was done by the use of GCAM (*Global Change Assessment Model*) as a tool for projecting future water demand by subsectors at country level. The study explored the water demand in 14 regions till 2095 under several social-economy scenarios [7].

The choice of energy- and water-intensive power plants either exacerbates the problem of water supply in water scare regions (such as the Northwest of China) or constrains operations of water-intensive power plants during water-shortage periods. As such, in addition to improve energy efficiency and reduce CO_2 emissions in power sector, it is also vital to evaluate water use in order to meet environmental targets, such as sustainable development of water resource. Considering energy and water issue in an integrated model could be found in Ref. [11]. To date, still only a few studies have considered the water demand of future power sector at China's national level, in a long period. Additionally, the assessment of impacts of both INDC and water constraint on China's power sector are rare.

In this paper, water module is integrated into a partial equilibrium energy environment model (*China TIMES model*) to integrate China's energy system and water system, to project the future water demand, and to assess the impacts of carbon and water constraints on power generation technology portfolio. It should give some insights for China's sustainable development, especially the reasonable utilization of water and energy resources.

The rest of the paper is organized as follows: Section 2 is a methodological section that describes the framework of China TIMES model integrated with water module, and the linkage of energy system and water system; Section 3 provides the basic assumptions and scenario definition; Section 4 lists the results of the model and the conclusions are provided in Section 5.

2. Methodology

2.1. Integrating water into the China TIMES model

The TIMES (*The Integrated MARKAL and EFOM System*) is a combination of the MARKAL (*Market Allocation Model*) and EFOM (*Energy Flow Optimization Model*) by the ETSAP (*Energy Technological System Analysis Program*) of IEA [12]. Based on China MARKAL [11,13,14], China TIMES model [15–19] was developed in 5-year intervals extending from 2010 to 2050 and has been proven as a powerful and reliable tool to study sustainable energy development and carbon mitigation for China. In this study, it is further improved by integrating a water module to consider water consumption for electricity generation and other energy processes. The model is calibrated based on a series of statistics and reports [20–23].

China TIMES incorporates the whole energy system and water module, including energy supply, energy conversion and transmission, end-use demand sectors, water supply and water utilization. Five demand sectors, agriculture, industry, commercial, residential (divided into urban and rural) and transportation, are considered and further divided into 43 sub-sectors in China TIMES [15]. The modelling using China TIMES determines the least-cost mix of technologies and fuels to meet the projected energy service demands for the 43 sectors for a given social economic development scenario.

This paper focuses on the power sector which is becoming more and more important toward low carbon society for China. Fig. 1 illustrates the linkage of China's energy system and water system in the China TIMES model. In the model's power sector, we consider more than 60 technologies including existing and advanced power generation technologies such as coal-, oil-, gas-fired power plants, nuclear, hydro, solar photovoltaic (PV), concentrating solar power (CSP), wind, biomass and other renewable generation technologies. Due to the detailed description of technologies in power sector in China TIMES, and due to the wide variation in the water withdrawal of different power generation technologies, we use a relatively detailed representation of water requirement for power generation technologies. For a specific technology, three types of cooling systems – once through cooling, recirculating cooling and air cooling – are considered. Water utilization in energy extraction, other conversion and processing is also considered in the model.

In the water module, two types of water resource are included into the water supply, namely conventional water (surface water and ground water) and non-conventional water (saline water and waste water). Electricity consumption for the water exploration, pumping and processing procedure is taken into consideration.

2.2. Energy-related water withdrawal and electricity requirement for water systems

In this study, the energy activity level and associated water withdrawal is endogenous determined by the optimization results of the integrated model. Power sector is an important water user in China, accounting for about 7% of the total in 2012. The water withdrawal in power sector is mainly affected by technologies' activity level, fuel type, and cooling type, as is shown in Eq. (1). Data on water withdrawal factors of different electricity generation technologies were gathered from various sources [24,25]. Several selected technologies are shown in Table 1. Notice that (1) the factor of PV and Wind are referring to cleaning water consumption; (2) nuclear plants are assumed to be installed on costal sites to use treated saline water for cooling.

$$WW_{Elc,t} = \sum_{\phi}\sum_{\varepsilon}(Elc_{\phi,\varepsilon,t} \times wc_{\phi,\varepsilon}) \tag{1}$$

where

$WW_{ELC,t}$: Water withdrawal in power sector in year t (m^3);

$Elc_{\phi,\varepsilon,t}$: The electricity production of technology ϕ, cooling type ε (MW h); the electric generation amount of each kind of technologies is endogenous optimized by the model;

$wc_{\phi,\varepsilon}$: The water withdrawal factor of power generation technology ϕ, cooling type ε (m^3/MW h), namely the water demand to produce one unit of electricity; it is an exogenous input and kept constant during the model period;

ϕ: The type of power generation technology;

ε: The type of cooling method, such as recirculating cooling, once through cooling and air cooling;

t: The time period.

Upstream sector is another important water user in China. The water demand in this sector is also related to the activity level and water withdrawal factor. In this model, we consider the following energy upstream technologies: coal mining and washing, oil and gas extraction, uranium extraction, coal-to-gas, coal-to-liquids, oil refinery, etc. Irrigation water for biomass growth is not included in the analysis. Table 2 gives the water withdrawal factors of some upstream process [26–28]. The water requirement in upstream sector is estimated as Eq. (2).