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China's energy-water nexus: Assessing water conservation synergies of the total coal consumption cap strategy until 2050

Yizi Shang [a], Pengfei Hei [b,*], Shibao Lu [c,*], Ling Shang [d], Xiaofei Li [e], Yongping Wei [f], Dongdong Jia [g], Dong Jiang [h], Yuntao Ye [a], Jiaguo Gong [a], Xiaohui Lei [a], Mengmeng Hao [h], Yaqin Qiu [a], Jiahong Liu [a], Hao Wang [a]

[a] State Key Laboratory of Simulation and Regulation of Water Cycles in River Basins, China Institute of Water Resources and Hydropower Research, Beijing 100038, China
[b] College of Life and Environmental Science, Minzu University of China, Beijing 100081, China
[c] School of Public Administration, Zhejiang University of Finance and Economics, Hangzhou 310018, China
[d] College of Computer and Information, Hohai University, Nanjing 211100, China
[e] CABR Technology Co., Ltd, China Academy of Building Research, Beijing 100013, China
[f] School of Geography, Planning and Environmental Management, The University of Queensland, Brisbane 4072, Australia
[g] State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Nanjing Hydraulic Research Institute, Nanjing 210029, China
[h] State Key Lab of Resources and Environmental Information Systems, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

HIGHLIGHTS

- The total coal consumption cap reduces coal output.
- The cap facilitates adjusting the structure of energy consumption.
- The cap has significant positive effects on the protection of water resources.
- Total coal consumption exceeds the coal mining scale constrained by total water use.
- A holistic approach to the challenges China faces related to water is critical.

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ABSTRACT

China's coal-based energy supply inflicts destructive damage upon the ecological environment, though it has simultaneously safeguarded the rapid development of China's economy in recent decades. To promote ecological recovery and accelerate the adjustment of its industrial structure, China is poised to fully implement a total coal consumption cap through the "13th Five-year Plan" (2016–2020). This study assesses the feasibility of this strategy from the perspective of water resources, exploring and predicting outcomes from 2012 to 2050. After first measuring the water resources demands for the life-cycle of coal, this study then analyzes the destructive effects on water resources from coal production through to consumption, before finally evaluating the water conservation synergy effects under different plans for capped coal consumption. The results reveal that implementing a total coal consumption cap could reduce the adverse effects on the water resources system due to coal mining, washing, conversion, and utilization by comprehensively promoting conservation and protection of water resources. The study directly compares the two cap strategies of "behave as usual" and "reinforced total consumption control," finding that neither of these strategies can totally satisfy China's existing requirements for water resources management. In future, China's total coal consumption will exceed the feasible scale of coal mining as restrained by total water use limits, and the required quantity of water for conversion and utilization of coal will also exceed its water use limit. Therefore, to achieve coordinated progress between the development of the coal-related industry and sustainable utilization of water resources, the Chinese government urgently needs to further reinforce total coal consumption controls and actively popularize the application of water-saving technology. In addition, the study estimates the damage to water resources due to China's coal consumption, determining the value of lost water resources per ton of coal consumption nationwide to be 52.76 yuan. If all of China's coal enterprises could apply water-preserving mining technology and make full use of mine water for production, the loss of water

* Corresponding authors.
E-mail addresses: yzshang@foxmail.com (Y. Shang), heipf06@mails.tsinghua.edu.cn (P. Hei), lu5111284@aliyun.com (S. Lu).

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resources nationwide per ton of coal consumption could be lowered to 40.91 yuan. Therefore, the study advocates the combination of a market price adjustment mechanism and a macro total control strategy to maximize the synergic benefits between energy and water resources in China.

1. Introduction

Water and energy systems are tightly intertwined. While water is used in all phases of energy production and consumption, energy is itself required both to extract, convey, and deliver water of appropriate quality for diverse uses and to treat wastewater prior to its return to the environment [1]. Historically, the interlinked water and energy challenges have been explored more in the energy production sector [2] and focused in the U.S. [3], Australia [4], and Spain [5], rather than in the global nexus, i.e., China (water and energy savings) [6,7], and the Middle East (water and energy linkages [8]; energy production and water technologies [9]). Recent studies have found that synergies between water and energy systems offer opportunities to integrate the benefits of new technologies [10]. Various energy-minimization and energy-use options in water technologies have been explored for different purposes [11]. Some authors have focused on the use of photovoltaic water pumping systems to mitigate CO_2 emissions [12], while others have analyzed desalination plants with photovoltaic or wind systems [13,14]. Moreover, desalination technologies [15] and modeling systems [16] have been developed to alleviate water scarcity in arid areas [17,18]. In hydrology, "water scarcity" is defined as the state in which the demand for water is greater than the available resources [19]. In reality, the accessibility of water resources is constrained not only by their physical availability, but also by economic drivers. Scarcity is also a water quality challenge [20], as water's usefulness for drinking, sanitation, irrigation, and industrial processes is relative to the physical, chemical, and biological properties of water. Therefore, water scarcity must be reviewed from the perspective of both the supply and demand [21].

Many studies have investigated CO_2 emissions related to energy development [22,23]. However, the energy sector not only contributes to an increase in CO_2 emissions, but also consumes a vast quantity of water [24]. More recently, a few studies have been conducted to analyze the nexus of energy and water by employing supply-to-demand equilibrium methods [25,26]. However, these methods have not been able to balance the development of both water and energy policies, and have focused on using the limited available water to secure energy production. Huston et al. [27] estimated the water use of coal-fired power plants in the U.S., finding that the coal-fired power industry's water withdrawal accounted for up to 40% of all freshwater withdrawal nationally. Burkhardt et al. [28] found that concentrated solar power systems consume more water (up to 4.7 L/kW h) than coal-fired power plants, although the application of dry-cooling systems can reduce the total water use by 77% during their life-cycle. In a case study of the coal-fired power generation industry, Mo et al. [29] warned that the choice of water-intensive techniques either exacerbates the problem of water supply in water-scarce regions or constrains operations of energy production activities during periods of water-shortages. Shang et al. [30] indicated that water use in arid areas, such as northern China, is likely to continue to increase, further complicating the management of both energy and water systems [31]. In another study, Shang et al. [32] suggested that the introduction of new technologies in the domains of energy and water could shift demands for both. In addition, policy developments addressing water rights and the water impacts of energy production are urgently needed to introduce additional incentives for energy-saving and water conservancy [33].

The significant nexus between energy and water necessitates integration of water issues in energy planning and an integration of energy issues in water planning and management [34]. Traditionally, the interaction between the energy and water sectors has been considered at the regional level throughout the world [35]. At the national level, energy and water systems have generally been developed, managed, and regulated independently [36]. With the importance of water in energy production and the increasing uncertainty of water supply [37], there is a growing need for a more coherent approach to develop relevant policies [38]. Nevertheless, the global water-energy decision-making landscape at the national level is rather complex [39], since there are strong regional differences in policy frameworks and objectives [40] and national water and energy policies have been developed independently [41]. Previously, little work has been undertaken to analyze the synergy between water and energy in the long term. In many cases, the synergies relate directly to the reliability and resilience of energy systems under changes in water resources [42]. Reliability and resilience, in turn, align with broad energy policy initiatives of the administration, such as the total coal consumption cap strategy [43], CO_2 emissions mitigation [44], and climate action plan [45]. Important work is wide-ranging, including the formulation of an energy development plan under water constraints, examination of the compatibility between existing energy and water policies using multiple scales, and calculation of the real costs of energy consumption with full consideration of its environmental impact.

The inappropriate planning system of energy development may cause severe ecological environment problems. China is suffering severe large-area haze pollution [46], perpetuated by the absence of environmental assessments during the planning stage of energy development [47]. It is universally well known that the haze is directly related to consumption of fossil energy, especially intensive coal consumption [46]. In the last century, China hastily built massive energy industries in its developed areas without scientific support [48]. Statistics show that the total coal consumption of the Beijing-Tianjin-Hebei Metropolitan Region, where China's capital is located, is 19 times greater than that of an equal area in the U.S., and the consumption of the Yangtze Delta area, the fastest developing region in China, reached up to 25 times more than that of an equal area in the U.S. [49]. Presently, the total emissions of all the major pollutants induced by fuel consumption in those areas have far exceeded their environmental capacities [50]. The Chinese government has recognized the seriousness of this problem [47], leading to their release, in October 2012, of the "White Paper on China's Energy Policy" [51], which stresses numerous energy challenges facing China's economic growth. In response to this publication, the National Energy Administration (NEA) established staged goals for total coal consumption targets (Version 2012) based on the Chinese government's goals of energy conservation and CO_2 emissions reduction, and by taking into consideration the distribution, reserve, and future consumption needs of coal [52].

The establishment of the total coal consumption cap will inevitably lead to synergy effects on water resources due to the nexus between energy and water [53]. In 2014, the Chinese government announced that the 13th Five-year Plan would include total coal

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