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Energy and water nexus in power generation: The surprisingly high amount of industrial water use induced by solar power infrastructure in China

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HIGHLIGHTS

- The high amount of industrial water use by solar power infrastructure is revealed.
- All the input items are inclusively inventoried as products of the economy.
- The industrial water use proves to be much higher than that in previous scoping.
- This magnitude doubles the unit lifetime water use of coal-fired generation system.

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ABSTRACT

A crucial aspect of the energy and water nexus is reflected with the revelation of the surprisingly high amount of industrial water use induced by plant infrastructure of a pilot solar power generation system in China, by means of a concrete hybrid of process analysis and Input-Output analysis. With an inclusive collection of all the input items as products of the economy, this scoping distinguishes from existing accountings that either overlook the construction stage or simply cover the plant infrastructure of solar power system as some primary materials. Supported by embodied water database from input-output analysis, the industrial water use induced by each input item is fully addressed. The industrial water use induced by the solar power plant infrastructure is revealed to be over one order of magnitude higher than that in previous scoping: this magnitude approximately doubles the life cycle industrial freshwater withdrawal of typical coal-fired power generation system for per unit amount of electricity generated. Under the 2020 scenario raised in the newly issued *13th Five Year Plan for Renewable Energy Development*, the annual industrial water use induced by solar thermal power infrastructure in China is accordingly estimated, in magnitude up to around 30% of the total industrial freshwater use in Beijing in the year 2014, one-fourth of that in Tianjin, and one-tenth of that in Shanxi, respectively. In the long term water-saving planning, the promotion of solar power installations is afforded further consideration.

1. Introduction

1.1. A review of energy-water nexus in the power sector

Energy and water, two widely-recognized critical resources for industrial development, are interdependently intertwined [1,2]. Water is directly or indirectly required in all types of power generation technologies for cooling purposes, steam generation, infrastructure manufacture, etc. [3]. Meanwhile, energy supply is indispensable in the process of freshwater withdrawal, allocation and treatment.

Power sector has for decades retained its position as an intensive user of water resources. For instance, around 40% of America's freshwater withdrawal flows into thermal power plants [4]. In China, home to a whopping one quarter of global installations in electric power [5], statistics suggest that water withdrawal of thermoelectric power plants amounts to around half of total industrial freshwater use [6]. Soaring electricity demand is supposed to take place on the globe in the near future, with an expected growth of 50% by 2030 than 2008 level [7]. In such condition, water shortage has become a major vulnerability to power generation.

Academia has directed fair attention to exploring the relationship between water and electricity in different nations and regions, such as the United States [8,9], China [10,11], United Kingdom [12],

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Mexico [13], Middle East and North Africa [14], India [15], Spain [16], etc. The existing studies could be categorized into two groups: macro-scale assessments and micro-scale ones.

On the macro scale, a number of studies carried out investigations on freshwater withdrawal or consumption induced by electricity sector globally [17], nationally [10,18,19], and regionally [20,21]. These works, mostly by means of input-output analysis, apply an overall manner to assessing the distribution of freshwater demand for electricity within different areas. On the global level, Holland et al. [17], predicated on an environmental extended MRIO (multi-regional input-output) global trade model, examined the consumptive freshwater use associated with international electricity production, with the revelation that freshwater consumption is substantially confined within the territorial boundaries where demand stems from. On the national level, with a hybrid of MRIO model and life cycle impact assessment method, Zhang and Anadon [18] identified the strikingly unbalanced spatial distribution of life cycle freshwater withdrawal and consumptive water use induced by electricity sector in China. On the regional level, Fulton and Cooley [20] analyzed the water footprint of electricity production in California between 1990 and 2012. Meanwhile, macro policy and institutional dimensions of energy and water nexus, in a wide spectrum from industrial water policy [22], technology innovation [23], decision making [24], energy tax [3], power planning [25] to energy conservation policy [26], win a certain coverage in the research. These policy studies, almost all of them, concentrate their focus on China, where shortage of water resources contradicts greatly with domestic electricity production. By squeezing power delivery, water scarcity suspends industrial development.

On the micro scale, water use intensities for different types of power generation technologies are explored. Dating back to almost four decades ago, early in 1978, Harte and El-Gasseir [27] presented the water requirements for some energy options in the United States. Later in 1994, Gleick [28] pioneered the investigation of water demand per unit power output for several generation alternatives across the globe, with a wide range from coal-based power, natural gas based power, hydroelectricity, nuclear power to photovoltaics and solar thermal electricity. Life cycle analysis as a bottom-up method is generally used. Afterwards, by focusing on different areas and using different data, subsequent studies come out in succession [29,30]. Thermoelectric power plants are noted to be the academic focus [29,31,32], thanks to the stunning amounts of freshwater withdrawal for steam cooling. For instance, Chang et al. [32] quantified the life cycle water use intensities of several typical types of coal-fired electric generation plants in China, while Zhai et al. [31] compared the water use of coal-fired generation system with and without carbon capture facilities in the US. More recently, other scholars, such as Macknick et al. [33], Meldrum et al. [34], Fthenakis and Kim [35], underpin their attention on comprehensive reviews of water withdrawal or consumption intensities for a variation of electricity generation technologies. In terms of water use induced by renewable power, though occasionally covered in some articles [36,37], it has been directed much fewer attention.

1.2. Water use of solar power

Renewable power, appreciated for the generally-accepted merits of energy-saving and low carbon emissions, enjoys increasing attention in recent decades. It has, according to international energy agency (IEA), in 2015 eclipsed coal as the biggest source of global power-generating capacity [38]. Solar power, among the various renewable alternatives, has experienced a burgeoning development. In 2015 alone, additional installations in solar power amount to a whopping one third of the 153 GW growth in renewable electricity capacity.

Though solar power has a wide coverage in academia, the focus underlines the associated energy use and carbon emissions [39,40]. Another critical aspect of solar power, water use, awaits further exploration. The concern is being vigorously fueled by the expectation of soaring solar power installations and the fact that water is becoming ever more scarce.

Questions that solar power system could be an intensive water user have been potentially raised in an official report by Electric Power Research Institute in US early in 1997 [41], backed by the estimations that solar power tower generation system and parabolic trough electric system, two forms of concentrating solar power (CSP) generating technologies, demand a dramatic water use of 3200 L/MWh and 2100 L/MWh in the operation phrase, respectively. Since then, evidence that solar power system, mainly solar thermal power plants, could use more freshwater resources than conventional fossil-fired power plants has been reported in a number of studies [42–45]. These works provide flexible results over the amount of freshwater use by CSP generating systems, ranging from 2900 L/MWh to 3800 L/MWh. With regards to solar photovoltaic system, the situation appears to be completely different. Analyses [41,43] suggest it is nearly free of water requirements, due to no direct water use during operation.

Nevertheless, what accounted in the above-mentioned studies, no matter for concentrating solar power system or solar photovoltaic power system, is confined to the operational freshwater use of the concerned system. The freshwater withdrawal induced by plant infrastructure is totally overlooked. In fact, the large amounts of resources use, or environmental emissions induced by solar plant infrastructure have find full reflection in existing evidences. For instance, Chen et al. [46] revealed that the energy use and carbon emissions induced by plant infrastructure of a concentrating solar power tower system could amount to the majority, actually over 80%, of the total induced throughout the lifetime. In this regard, water use induced by plant infrastructure, as another crucial aspect of the solar power, calls for full attention.

In 2010, Fthenakis and Kim [35] reviewed the lifetime uses of water by several types of renewable power plants in the U.S., including CSP, solar photovoltaic, wind biomass, geothermal, etc. The findings are that the upstream freshwater withdrawal by solar photovoltaic infrastructure could reach an amount of 1470 L/MWh, which is several orders of magnitude higher than the amount of direct freshwater use (14 L/MWh) required in the operation stage. Afterwards, Heath and his colleagues [47,48] have dedicated a series of efforts in life cycle assessment of CSP systems, both power tower concentrating solar plant and parabolic trough concentrating solar power plant. The results suggest that plant infrastructure of the power tower concentrating solar plant is responsible for around one-third of the life cycle water use, while that of the parabolic trough concentrating solar power plant with dry-cooled design holds for nearly one half of the total water use.

These studies equip us with preliminary and valuable knowledge into the remarkable water use by solar power infrastructure. While in the meantime, a general principle in previous practices is to decompose the components of plant infrastructure into some primary materials (steel, iron, concrete, etc.). The justice is upon ponderation as what accounted are some primary materials that constitute the component, neither the supply inputs nor primary materials for the supply of the component, not to mention the component itself. Manufacturing information finds no reflection in previous accounting. The same primary materials could be an assembly of some other system with quite different components.

The objectives of this study are multiple. For the first time, the water use induced by solar power infrastructure is separately investigated. By inventorying inclusively all the associated input items in the construction stage, this study puts a distance from previous works that are based on some primary materials for plant