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Life cycle water use of a biomass-based pyrolysis polygeneration system in China

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HIGHLIGHTS

- Life cycle water use intensity of a Chinese biomass pyrolysis system is 3.89 L/MJ.
- Data is for the first moving-bed biomass pyrolysis commercial plant in China.
- Biomass production contributed to majority of the life cycle water use.
- The biomass pyrolysis system is less water intensity than other biomass energies.
- Water use is large if the technology applied widely to meet the national plan.

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ABSTRACT

Water is essential for bioenergy production. Characterized as low carbon technology, crop-based bioenergy technology witnesses rapid development, inevitably putting pressure on global water resources. Therefore, it is crucial to carefully assess bioenergy technology's overall impact on scarce water source for a sustainable bioenergy future. In this regard, this study aims to evaluate the life cycle water use of bioenergy from agricultural residues via the first pilot moving-bed pyrolysis polygeneration system in China. By using a tiered hybrid life cycle assessment, both direct and indirect water use are calculated. Results show life cycle water use is 3.89 L H_2O/MJ and agricultural process dominates the total water use. Scenarios analysis shows different feedstock allocation ratios during agricultural production have striking influence on water use intensity. In addition, the choice of feedstock is another important influential factor. Under the 2020 Scenario in China's *13th Five Year Plan*, if all the bioenergy target could be met by polygeneration the estimated annual water use will be 6.6 billion m^3, in magnitude up to around ten times the total water consumption in Denmark in 2013. In global scenario of potential feedstock available in 2060, the estimated water use for bioenergy produced by polygeneration will be 179–369 billion m^3. Although the water use intensity of bioenergy production from agricultural residues by polygeneration is lower than that for other biomass conversion pathways, it is still higher than water intensity of conventional fossil energy products. Large-scale bioenergy production will have macroscopic effects on water demand. Finally, suggestions such as selecting high water-efficient biomass feedstock and reinforcing water-saving irrigation management to minimize water use in agriculture stage are proposed.

1. Introduction

1.1. General background

Biomass energy plays a critical role in tackling issues of energy supply security and climate change at global and national scales [1]. Currently, as the most widely used alternative to fossil energy, bioenergy accounts for roughly 9% of world total primary energy supply [2]. Nevertheless, concerns have been raised in recent years not only about biomass related air pollution and fossil energy costs [3–5], but also its impact on available water resources. Both biomass cultivation and conversation consume a large amount of water [6,7]. Globally, agricultural sector is responsible for 70% of water extraction worldwide and this figure is predicted to rise in the coming decades [8],

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against the background that freshwater is scarce in many countries such as South Africa, China and India [9]. A large-scale expansion of biomass production would lead to a large increase in evapotranspiration, this could lead to further enhancement of an already stressed water situation [10]. Consequently, water shortage will be a great challenge for future bioenergy development. In this regard, it's essential to facilitate sustainable water management in bioenergy based on the knowledge about the overall water use by bioenergy technologies.

A broad set of methods has been introduced and to account water use at global, national, regional and even corporate levels [11,12]. As a typical energy substitution feedstock, water use of biomass has been calculated by many researchers, focusing on biomass agricultural production. Chapagain and Hoekstra [13] made the first agricultural products water use dataset for each nation of the world. Subsequently, various studies conducted global and regional water use analysis of food crops and energy crops [14–17]. It was found that the water use of bioenergy is 70–400 times larger than that of a mix energy from non-renewable sources (excluding hydropower) [14]; notably, within the category of biomass for energy purposes, differences in water use intensity are large due to various crop types, agricultural production situations, climatic circumstances as well as local factors [16,17]. All these studies significantly raised the awareness of biomass-related water resource consumption. Therefore, prior to large-scale application of bioenergy from various biomass in different regions of the world, water use of different bioenergy utilization technologies should be evaluated firstly to illustrate the sustainability in a water perspective.

1.2. Literature review

To give a comprehensive understanding of water use of bioenergy, numerous studies have been conducted to assess bioenergy system efficiency in terms of water use. The total water use by bioenergy system consists of water used during biomass agricultural production and that in the subsequent conversion processes which transform biomass into energy products [18], e.g. heat and electricity via combustion, biofuels such as bio-ethanol and biodiesel, syngas via gasification and pyrolysis, biogas from fermentation, and biochar [19].

In general, the above mentioned products can be classified as the first-generation bioenergy and second-generation bioenergy [20]. First-generation bioenergy mainly are present available biofuels produced using conventional technology, i.e., fermentation of carbohydrates (starch and sugar) into ethanol; extracting and processing oil from oil crops into biodiesel [21]. Many studies have been carried out to figure out the water use for first generation bioenergy production. Chiu et al. [22] and Jasonm et al. [23] found out that biofuels derived from corn require more water compared with other feedstock, and there is a wide variation in water requirement for bioethanol due to the regional irrigation practices in the US. Mangmeechai et al. [24] studied the life cycle water footprints of molasses-based ethanol and cassava-based ethanol in Thailand and the results show approximately 99% of the water footprints is attributed to crop cultivation. Singh et al. [25] highlighted that a significant amount of water is required by processes including feedstock production, transportation and conversion for biofuels from wheat in Canada. Moreover, a scenario analysis suggested that southern Alberta would not have enough water to meet the high irrigation water requirements due to the dry climate. Similar efforts have been made by Dominguez-Faus et al. [26], who looked into the water requirement for energy production from different processes. The results showed the water consumption and agrochemical use during biofuel production could adversely impact both availability and quality of previous water resource.

All these existing studies revealed first-generation bioenergy's huge demand on water and identified that the majority of water consumption occurs during feedstock cultivation stage [27–29]. Since the first-generation bioenergy has limited ability to meet the targets of energy demand under the constraints of land and water resources [30], researchers have shifted their attention to more sustainable second-generation bioenergy. Second generation feedstock derived from large amounts of biomass residues (e.g., agriculture residue and forest residue) are identified as the most abundant form of biomass available worldwide. In addition, feedstock sources like agricultural and forestry residues, which are usually considered as byproducts that do not require extra irrigation, are expected to be less water intensity [20].

Water use by second-generation bioenergy already attracted some researchers' attention. Mishra et al. [31] investigated the life cycle water requirements of ethanol from corn grain and crop residues. The results showed that compared with corn grain-based ethanol, life cycle water requirements from corn residues is 13% lower, as water use during corn cultivation entirely is assigned to corn grain. Chiu et al. [32] discovered that when using bagasse and rice straw as raw materials, the amount of water use is considerably smaller than that of the first-generation bioethanol, mainly because the water use of bagasse and rice straw is allocated to the main product, rice and sugar cane. Singh et al. [33] developed an integrated spreadsheet-based model to estimate total water requirement for twelve biomass conversion pathways, and found that corn stover-based and wheat straw-based ethanol production were the most water-efficient pathways. Wong et al. [34] studied water use of hydrogenation derived renewable diesel (HDRD) from forest residues, agricultural residues and forest biomass via pyrolysis and hydrothermal liquefaction. The results suggest that agricultural residues (i.e., straw from wheat, oats and barley) were more water efficient than forest biomass and residues. Recently, Mathioudakis et al. [35] calculated the water use of second-generation bioenergy. This research concluded that it is relatively water efficient to apply crop residues rather than miscanthus and wood; to convert crop residues into pyrolysis oil rather than bioethanol. All the aforementioned studies have provided useful information to understand the water requirements by different bio-energies and technologies. It suggests that agricultural residues could be served as a promising near-term bioenergy feedstock option for both carbon neutral and less water-intensive technology.

1.3. Goal and significance

Biomass and waste are already a significant global energy source, total consumption of biomass and waste resources by end use is 51 EJ in 2015 [36]. As one of the world's major agricultural countries, the amount of crop residues produced in China was 600–800 million tons in 2015 and over half of which could be utilized as energy source [37]. Pyrolysis polygeneration is a promising conversion technology which has advantages such as high energy conversion efficiency and economic profitability and now there have been several demonstration projects in operation in China [38]. Recently, Kuntal et al. [39,40] assessed the life cycle environmental impact of agro-based polygeneration and proved that polygeneration is a better option than single-utility generation for its higher resource utilization efficiency, flexibility and environment-friendliness. According to the forecasted scenario of International Energy Agency (IEA), to control the global temperature rise within of 2 °C, the proportion of bioenergy utilization will increase to 17% in 2060 [2]. The development potential of bioenergy is huge, and future large-scale application of bioenergy in worldwide will potentially have impact on water resource. However, there have been very few detailed studies on water use of bioenergy from pyrolysis polygeneration. Thus this study intends to fill the gap in knowledge on the life cycle water use for converting the agricultural residues into bioenergy via pyrolysis polygeneration.

The novelties of this research are elaborated as follows. Firstly, Biomass-based pyrolysis polygeneration is an advanced bioenergy technology for delivering of multiple energy outputs in an efficient way. What's more, it has good applicability for worldwide utilization due to its adjustable process capacity and compatibility of various feedstock. However, water use evaluation of pyrolysis system is still a missing