The Water Footprint of Bioethanol

Chung Chia Chiu, Wei-Jung Shiang, and Chiuhsiang Joe Lin

Abstract—Concerns regarding energy security and climate changes have stimulated the development of renewable energy. Various countries have actively invested in research and development programs for renewable energy to reduce the dependence on fossil fuels. Bioethanol is the most commonly used biofuel in transportation. However, the trend of substantially increased transportation biofuel usage has caused competition over freshwater resources to increase. After energy problems, water resources are another critical topic worthy of exploration. This study involved analyzing the results of 150 studies regarding water footprints (WFs) between 2005 and 2013. Among the studies analyzed, only 4 involved discussion of WFs of bioethanol products. The bioethanol WFs in the various studies ranged from 790 L H₂O/L EtOH to 11030.4 L H₂O/L EtOH. The minimal value was observed in sugar beets in a French study, and the maximum was observed in ethanol from molasses in Kanchanaburi, Thailand. WF expressions of bioethanol may vary according to the produce category, climate in which produce is grown, soil characteristics, and various production volumes or consumption methods. In addition, the total WF is not the only criterion for selecting the raw materials of bioethanol production. Produce that possesses a high green WF content and accommodates local climates should be selected with priority. The research results can provide a guideline for following studies in the field of bioethanol WF. Furthermore, the results can be used as a critical reference for selecting raw materials of bioethanol production.

Index Terms—Biofuel, bioethanol, water footprint (WF), biomass.

I. INTRODUCTION

Concerns about energy security and climate changes have stimulated the development of renewable energy [1]. Various countries have eagerly invested in research and development programs for renewable energy to reduce the dependence on fossil fuels. The European Union (EU) established a goal of replacing 10% of transportation fuel with renewable energy by 2020 [2]. Using bioenergy as a major substitute fuel for transportation has received the most attention from researchers. According to the International Energy Agency (IEA), by 2030, bioethanol and biodiesel will contribute 7% and 3% to the total bioenergy demand, respectively [1]. Bioethanol is the most commonly used biofuel.

After the oil crisis in the 1970s, the Brazilian government launched a National Alcohol Program to use sugar cane as the

primary energy crop for alcoholic fuel research, development, and production. Based on strong promotion by the government, improvement of sugar cane species innovation and cultivation technology is being conducted actively. The total production volume of bioethanol in Brazil achieved approximately 32.5 billion L by 2011, 90% of which was used for domestic consumption in Brazil [3]. In December 2007, the United States proclaimed the implementation of the Energy Independence and Security Act (EISA 2007) to elevate fuel efficiency standards and reduce dependence on crude oil. EISA 2007 involves a standard to increase the volume of biofuel alcohol use by more than 6 times, reaching an annual use volume of 36 billion gallons by 2022 [4]. Gerbens-Leenes and Hoekstra (2011) [5] reported that according to the EU, the mandatory volumes of renewable energy and biofuel energy used in road transportation will reach 10% in 2020. To reduce the dependence on petroleum import, the government of Thailand proposed a policy to use alcohol fuel as renewable energy and encouraged production of bioethanol. Currently, the two primary types of biomass used in Thailand for producing ethanol are sugarcane molasses and cassava [6]. The Vietnamese government is actively planning to use straw, a byproduct of paddy rice, as the material for producing bioethanol without degrading soil fertility or changing the current agricultural and husbandry styles. According to the Earth Policy Institute (2012) [7], the global ethanol production volume was 22,742 million gallons in 2011, 87.4% of which was produced by the United States and Brazil. The primary source of production of ethanol in the United States was maize. In Brazil, the primary product was sugarcane ethanol. The global bioethanol production volume increased from 13,089 million gallons in 2007 to 22,715 million gallons in 2012, indicating a 74% increase within 5 years. This increase indicated the value of bioethanol in renewable energy production.

The tendency toward increased application of transportation biofuels has increased the competition over freshwater resources [8]. The IEA predicted that in 2030, the global annual WF of biofuels will be 10 times that in 2005. Because of the global increase in water consumption tendencies for biofuel production, extra pressure from freshwater resources will emerge. Apart from energy problems, water resource-related problems are a critical and worthy of exploration.

Hoekstra proposed the concept of water footprints (WFs) in 2002 [9]. WFs refer to calculating three key water elements based on the water volume directly and indirectly used by consumers or producers. The three key water elements consist of blue, green, and grey water. Generally, the blue WF is an indicator of the amount of fresh surface water or groundwater consumed in producing goods and services. The blue WF is the amount of water evaporated, incorporated into the product or returned to a different location or in a different

Manuscript received October 22, 2014; revised January 25, 2015.

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time period from where it was withdrawn. The direct water footprint can include water footprint of manufacturing activities and overhead, such as water footprint of offices, canteens, and horticulture. The green WF is the consumption index of green water resources, which refers to rain water that falls and remains on the ground without flowing away or becoming part of groundwater. It is relevant for agricultural and forestry products (products based on crops or wood), and refers to the total rainfall or soil moisture lost through evapotranspiration by plants plus the water incorporated into the harvested crop. In other words, green water is absorbed by plants, enabling forests to grow and crops to be productive. The grey WF is a measure of pollution and is expressed as the volume of water required to assimilate the pollutant load to meet ambient water quality standards. The pollutant that requires the largest assimilation volume is referred to as the critical pollutant and is used to calculate the grey water footprint [9]. According to the WF assessment manual published by the Water Footprint Network (WFN) [10], a WF is an indicator used to measure water use based on the perspectives of freshwater resource use and pollution. The measurement is about the volume of water used instead of traditional quantity of water. Direct and indirect water use by producers and consumers are measured extensively to provide information on how consumers or producers use freshwater resource systems, as shown in Fig. 1.

Fig. 1. Schematic representation of the components of a water footprint. The nonconsumptive part of water withdrawal (the return flow) is not part of the water footprint; contrary to the measure of “water withdrawal,” the “water footprint” includes green and grey water and indirect water use [10].

Based on human energy demands and the pressure of natural water resource competition, this study aimed to explore the main factors influencing the WFs of bioethanol and determine the methods for reducing competitive pressure over water resources while producing bioethanol. The method adopted was a review of papers concerning WFs of bioethanol.

II. PAPER SURVEY AND EXPERIENCE SHARING

A. Paper Survey of Water Footprint for Bioethanol

The increased production volume of bioethanol noticeably increased the use of water resources. To understand the WFs of ethanol, a total of 150 studies regarding WFs between 2005 and 2013 were collected from databases such as WFN, ScienceDirect OnSite, and ScienceDirect Online. Among these studies, 13 were relevant to bioethanol; four of these 13

studies involved discussions of WFs of bioethanol products, six involved discussions of WFs of bioethanol applications, and three involved discussions of WFs of the biomass raw materials used to produce bioethanol. This search revealed that research on WFs of bioethanol has not been conducted extensively.

According to studies relevant to WFs of bioethanol, the main factors influencing bioethanol WFs are crop types, agricultural practices, and climate. Gheewala *et al.* [11] investigated the bioethanol policy in Thailand and proposed a report using cassava, sugarcane, and sugarcane molasses as raw materials. The report indicated that the WFs of bioethanol in Thailand ranged from 1396–3105 L H₂O/L EtOH. Cassava ethanol exhibited the highest WF (2374–2841 L H₂O/L EtOH), followed by sugarcane (1396–2196 L H₂O/L EtOH) and sugarcane molasses (1976–3105 L H₂O/L EtOH). The study indicated that although WF contribution during bioethanol processing was low, conserving water using engineering methods was encouraged.

In a study investigating the molasses ethanol WFs in Kanchanaburi and Supanburi, Thailand, Chooyok *et al.* [12] revealed that the green, blue, and grey WFs of molasses ethanol in Kanchanaburi were 849.7 m³/ton, 209.6 m³/ton, and 45.0 m³/ton, respectively. In Supanburi, the green, blue, and grey WFs were 708.3 m³/ton, 102.9 m³/ton, and 64.8 m³/ton, respectively. These results suggested that the crop cultivation region, unique regional climate, soil, and date of cultivation effectively influenced the value of WFs. Moreover, effective water use management positively affected the cultivation of regional crops.

In a study on WFs of sweeteners and bioethanol from sugar cane, sugar beet, and maize [13], Gerbens-Leenes and Hoekstra (2009) [13] indicated that the WF of ethanol from sugar cane in Brazil was 2450 L H₂O/L EtOH, in the United States was 2775 L H₂O/L EtOH, and in India was 2995 L H₂O/L EtOH. The weighted global average was 2855 L H₂O/L EtOH. The WFs of ethanol from sugar beet for the main producers were as follows: 790 L H₂O/L EtOH for France; 845 L H₂O/L EtOH for Germany; 1290 L H₂O/L EtOH for the United States; 2075 L H₂O/L EtOH for the Russian Federation; and 2780 liter/liter for the Ukraine. The weighted global average WF was 1355 L H₂O/L EtOH. The WF of ethanol from maize in the United States was 1220 L H₂O/L EtOH. The weighted global average WF was 1910 L H₂O/L EtOH. The results indicated that the factors causing differences in WFs were primarily crop water requirement and production volume. The variable of crop water requirement was determined based on various factors, such as the type of crops, climate, and soil characteristics. In certain countries, such as Egypt, the crop water requirement was determined by irrigation. The sugar beet, which is increasingly used in Japan, requires little irrigation. The amount of earnings yielded was determined by the difference between growing conditions and national agricultural regulations. Gerbens-Leenes and Hoekstra (2009) [13] also indicated that several of the high WFs could be reduced if more efficient approaches were adopted.

In a study regarding the water footprint of bioenergy [14], Gerbens-Leenes *et al.* (2009) [13] used 12 crops that most substantially contributed to bioenergy among global

agricultural productions as the raw materials for bioenergy production, comprising barley, cassava, maize, potato, rapeseed, paddy rice, rye, sorghum, soybean, sugar beet, sugarcane, and wheat. Sugar beet and potato were the most favorable crop materials for bioethanol production (1388 L H₂O/L EtOH and 2399 L H₂O/L EtOH, respectively), followed by sugarcane (2516 L H₂O/L EtOH). Sorghum was the least favorable raw material (Table I). Rapeseed and soybean were primarily used to produce biodiesel.

TABLE I: COMPARISON OF WFs OF BIOETHANOL MADE OF VARIOUS BIOMASSES (L H₂O/L EtOH)

Raw material	WF _{blue}	WF _{green}	WF
Sugarcane	1364	1152	2516
Paddy rice	1641	2835	4476
Maize	1013	1557	2570
Sugar beet	822	566	1388
Cassava	420	2506	2926
Potato	1078	1321	2399
Barley	2083	1644	3727
Rye	1846	2143	3990
Wheat	2873	2073	4946
Sorghum	4254	5558	9812

B. The Development of Second-Generation Bioethanol in Taiwan

Biofuels can be categorized into four generations based on the various stages of biofuel development. They are described as follows: First-generation biofuels are primarily made from arable crops and feature advantages such as mature technology and competitive prices. Nevertheless, the problems generated include competition with the public regarding crops and arable lands, and the high price volatility of raw materials. In the production of second-generation biofuels, the drawbacks of first-generation biofuel production were improved; however, the technology is still immature. Third- and fourth-generation biofuel production involves technologies that are still being developed and have disadvantages such as noncompetitive production costs and higher capital requirements compared to those of first-generation biofuel production.

The second-generation bioethanol demonstration plant in Taiwan. Located in Northern Taiwan, The plant was designed to process one ton of raw materials daily; the raw materials primarily comprised rice straw and bagasse from Central Taiwan, and the both raw material per ton can produce about 200 and 220 liters of bioethanol.

To produce the bioethanol, the following operating procedure is adopted at the plant: First, the raw material is shredded and treated through acid-catalyzed steam explosion. Subsequently, a simultaneous saccharification and fermentation process is employed to transform the raw material into bioethanol. By extruding and filtering the raw bioethanol and allowing it to dehydrate through distillation, a bioethanol that was 99.5% pure is produced. Fig. 2 shows a diagram of the second-generation bioethanol production process.

Calculations the WF of second-generation bio-ethanol, with rice straw and bagasse refined second-generation bio-ethanol in Taiwan, the WF significantly lower than the first-generation bio-ethanol, the main reason is the use

biomass crop residues, and the WFs of these raw materials has a great part of the account has been calculated or assigned to the first use.

Fig. 2. Production process of the second-generation bioethanol.

III. DISCUSSION

A. WFs of Bioethanol

Biomass energy, which belongs to renewable energy, began to receive attention as a replacement or method for reducing dependence on fossil energy. Plants with high sugar or starch content were used to produce bioethanol. A trade-off relationship exists between bioethanol and freshwater resources. Studies have demonstrated that the WFs of bioethanol ranged extensively from 790 L H₂O/L EtOH (sugar beet in France) to 11030.4 L H₂O/L EtOH (molasses ethanol in Kanchanaburi, Thailand). In addition, bioethanol exhibited varying levels of WF based on the type of raw materials used. For example, the WF of sugarcane bioethanol was 2450 L H₂O/L EtOH (Brazil); however, the WF of sugar beet bioethanol was 790 L H₂O/L EtOH (France). Bioethanol produced using the same raw material grown in different places may also exhibit differing WFs. For example, the WF of sugarcane bioethanol was 2450 L H₂O/L EtOH in Brazil, but that in India was 2995 L H₂O/L EtOH. The most prominent difference between WFs and other environmental indicators (e.g., carbon footprints and ecological footprints) is that WFs vary based on crop type, climate of the location where the crops are grown, soil characteristics, production volume, and consumption methods. These differences also cause varying WF performance among crop-based products.

B. Selection of Raw Materials of Bioethanol

Numerous studies have indicated that WFs of bioethanol and produce-related products were primarily observed in the cultivation and growing stages. Compared with the WFs in these stages, the water consumption used for industrial production of the products was low enough to be ignored [15]–[17]. Researchers should explore whether this indicates that the biomass crops with minimal WFs should be selected as bioethanol raw materials. In a climatic or geographical environmental region, human beings and animals use the water resources of the region in the same macroscopic environment. Therefore, the WF composition of raw materials merits particular attention. The blue water use of biomasses indicates that the water required for crop growth is insufficient and manual irrigation is required as a supplement. The increase of this item value represents that crop development and human living demands for water resources have become increasingly competitive. Grey water represents the pollution of water resources. A high concentration of pollutants requires more blue water for dilution, which also increases competition over water resources. Green water represents the water contained in soil after precipitation,

which is not surface water or ground water. The water in this section is the critical basis of plant survival. However, green water is not an obvious choice for human living demands. Therefore, crops with relatively high green WF content that are suitable for local climates should be selected preferentially as raw materials. For example, when provided a choice between two types of sugarcane with $500 \text{ m}^3/\text{ton}$ WF, where one choice is Indian sugarcane ($\text{WF}_{\text{green}} = 100 \text{ m}^3/\text{ton}$, $\text{WF}_{\text{blue}} = 350 \text{ m}^3/\text{ton}$, $\text{WF}_{\text{grey}} = 50 \text{ m}^3/\text{ton}$), and one choice is Brazilian sugarcane ($\text{WF}_{\text{green}} = 360 \text{ m}^3/\text{ton}$, $\text{WF}_{\text{blue}} = 100 \text{ m}^3/\text{ton}$, $\text{WF}_{\text{grey}} = 40 \text{ m}^3/\text{ton}$), the Brazilian sugarcane is more favorable than is the Indian sugarcane because of the high green water content, if other factors are not considered. This indicates that total WF cannot be used as the sole standard to select bioethanol raw materials. The component contents must also be considered.

C. Current Difficulties and Prospects of Bioethanol

Currently, the production cost of bioethanol cannot compete with massively produced fossil fuels. For example, in the United States, the cost of converting maize into alcohol and mixing the alcohol with biomass fuels, according to EU calculation, is 5% higher than that of traditional gasoline, if no subsidies or exemptions are provided. In addition, to satisfy the economic requirements of biofuels, a considerable area must be used to plant biomass crops to provide raw materials for conversion, which reduces the space for planting food crops and freshwater requirements. For example, in Brazil, sugarcane has been planted to produce alcohol. To increase sugarcane raw materials, land was explored, which indirectly influenced the growth area of rain forests, thus adversely affecting the global environment. To resolve the problems of first-generation bioethanol raw material crops competing with people for food and competing with food crops for land, one solution would be using waste agricultural byproducts (e.g., straw and waste molasses) as the raw materials for producing bioethanol (i.e., second-generation bioethanol). For example, straw is the type of agricultural waste with the largest amount globally. In China, 0.65 billion tons of straw are produced annually. If this amount of straw is processed by burning, an extremely terrible haze problem will occur. However, if 0.1 billion tons of the 0.65 billion tons of straw are used to produce bioethanol for fuel, 20 million tons (approximately 0.34 million gallons) of bioethanol can be produced annually based on a 20% conversion rate.

Although second-generation bioethanol can partially solve the problems (i.e., competition for food with people and for land with food crops) of first-generation bioethanol, second-generation bioethanol cannot be produced commercially because of limited production technology and bottlenecks in conversion rates. Future studies should examine methods for improving the conversion rate and explore increasing biomass raw materials. The emergence of shale oil is likely to extend the usable duration of fossil fuels and, from the perspective of environmental improvement, provide additional time for the development of biofuels.

IV. CONCLUSION

Concerns regarding energy security and climate changes

have stimulated development of renewable energy. Various countries have actively invested in research and development programs of renewable energy to reduce the dependence on petroleum. The EU planned to replace 10% of the total transportation fuels with biofuels by 2020. Numerous countries, such as the United States, Brazil, and Thailand, have actively developed bioethanol to reduce the dependence on fossil fuels. The rapid growth of global bioethanol production volume has caused an increase in water use, which causes additional pressure on freshwater resources. Therefore, after energy problems, water resources are the second most critical problem worthy of exploration.

In this study, a total of 150 studies regarding WFs were collected. However, only 4 involved discussions of the WFs of bioethanol products. In these studies, the WFs of bioethanol ranged from $790 \text{ L H}_2\text{O/L EtOH}$ (sugar beet in France) to $11030.4 \text{ L H}_2\text{O/L EtOH}$ (molasses ethanol in Kanchanaburi, Thailand). Bioethanol exhibited varying WF performance based on the type of crops, climate of the location where the crops were grown, soil characteristics, production volume, and consumption methods. Moreover, the total WF value cannot be used as the sole criterion for selecting raw materials of bioethanol; instead, the crops with high green WF content that can accommodate for local climates should be preferentially considered.

The current production cost of bioethanol cannot be compared to that of massively produced fossil fuels. First-generation bioethanol has encountered several problems, including competition over food with people and competition over land with food crops. Second-generation bioethanol cannot be produced commercially because of limited production technology and bottlenecks in conversion rates. Future studies should investigate methods for increasing the conversion rates and explore new potential biomass raw materials. The emergence of shale oil can likely extend the usable duration of fossil fuels; however, from the perspective of environmental improvement, shale oil can provide additional time for biofuel development. The results of this study can provide guidance for future researchers in the field of bioethanol WF, and can be used as a crucial reference for selecting raw materials for bioethanol production.

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