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# Water Footprints of Cassava- and Molasses-Based Ethanol Production in Thailand

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The Thai government has been promoting renewable energy as well as stimulating the consumption of its products. Replacing transport fuels with bioethanol will require substantial amounts of water and enhance water competition locally. This study shows that the water footprint (WF) of molasses-based ethanol is less than that of cassava-based ethanol. The WF of molasses-based ethanol is estimated to be in the range of 1,510–1,990 L water/L ethanol, while that of cassava-based ethanol is estimated at 2,300–2,820 L water/L ethanol. Approximately 99% of the water in each of these WFs is used to cultivate crops. Ethanol production requires not only substantial amounts of water but also government interventions because it is not cost competitive. In Thailand, the government has exploited several strategies to lower ethanol prices such as oil tax exemptions for consumers, cost compensation for ethanol producers, and crop price assurances for farmers. For the renewable energy policy to succeed in the long run, the government may want to consider promoting molasses-based ethanol production as well as irrigation system improvements and sugarcane yield-enhancing practices, since molasses-based ethanol is more favorable than cassava-based ethanol in terms of its water consumption, chemical fertilizer use, and production costs.

**KEY WORDS:** Water footprint, ethanol production, water resource management, alternative energy policy.

## INTRODUCTION

Petroleum consumption accounted for approximately 35–40% of the total energy consumed in Thailand (Ministry of Energy 2011). Due to volatile global oil prices as well as an attempt to reduce oil dependency, the Thai government has been promoting the renewable energy industry as well as stimulating the consumption of renewable energy in the country through a number of governmental policies such as oil tax exemptions for consumers, cost compensation for ethanol producers, and crop price assurances for farmers (Sora et al. 2010). The country's renewable energy development plan lists three bioethanol production targets. The short-term target is 3M liters of ethanol per day (2008–2011), the mid-term target is 6.2M liters of ethanol per day (2012–2016), and the long-term target is 9.0M liters of ethanol per day (2017–2022) (Department of Alternative Energy Development and Efficiency 2008, 2012).

Despite rapid growth in biofuel production worldwide, sufficient information on water related to its production is required (Ridley et al. 2012). Replacing transport fuels made from crude oil with biofuels made from crops will take a lot of effort and will require substantial amounts of water, which would enhance water competition (Chiu and Wu

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2012; Dominguez-Faus et al. 2009; Engelhaupt 2007; King and Webber 2008; Mishra and Teh 2011; Scown et al. 2011). The global annual biofuel water footprint (WF) will increase from 90 to 970 km$^3$/year in 2030 (Gerbens-Leenes and Hoekstra 2011; Lienden van 2010). The WF of ethanol production was reported to be within the range of 1,550–3,450 L water/L ethanol (see Fig. 1). The results seem to vary greatly depending on crop type, plantation method, and irrigation system. The WF of molasses-based ethanol in Thailand was in the range of 985–2,761 L water/L ethanol; the WF of cassava-based ethanol was 1,265–3,876 L water/L ethanol. Pongpinyopap and Mungcharoen (2011) reported that water use in a cassava plantation equaled to 12,739 m$^3$/ha; of this, 8,834 m$^3$/ha (69%) was from rainfall and 3,905 m$^3$/ha (31%) from irrigated water. With a yield of approximately 21 tons/ha, water use for the cassava plantation was 599.5 m$^3$/ton. At an ethanol plant, water use for mixing, fermentation, and distillation processes was 1.024, 0.003, and 0.275 m$^3$/ton, respectively. The study assumed that 1 ton of cassava can produce 155–210 L of ethanol. Thus, water use for cassava-based ethanol production was estimated to be 2,861–3,876 L water/L ethanol. The UNESCO-IHE (2008) reported on the WFs of molasses- and cassava-based ethanol produced in Thailand. This study assumed that water use in ethanol plants could be neglected. The WF of molasses was 119 m$^3$/GJ (64 m$^3$/GJ gray water and 55 m$^3$/GJ blue water) or 2,761 L water/L ethanol, while the WF of cassava was 87 m$^3$/GJ (79 m$^3$/GJ gray water and 8 m$^3$/GJ blue water) or 2,059 L water/L ethanol. The FAO (2010a, b) estimated the WFs of molasses- and cassava-based ethanol in Thailand at 1,550 and 2,168 L water/L ethanol, respectively. Gerbens-Leenes and Hoekstra (2011) estimated the respective world average WFs of molasses- and cassava-based ethanol at 2,516 and 2,926 L water/L ethanol.

Inconsistency of framework for WF calculation causes unfair comparison among different studies. For instance, some studies did not report on the water used in ethanol plants as well as indirect water use associated with ethanol production. This knowledge is important for water management because the water used in an ethanol plant is generally withdrawn from irrigation (blue water) and is different from water used for crops, which is primarily from rain (green water). Moreover, there are conflicting results; for example, the study of the UNESCO-IHE reported that molasses-based ethanol production consumed a larger amount of water than cassava-based ethanol. On the contrary, the FAO reported that the production of cassava-based ethanol required a larger volume of water.

The aim of this study is to quantify the WFs associated with the production of molasses- and cassava-based ethanol in Thailand to understand their potential impacts. Both direct and indirect water consumption values are reported. In addition, policy recommendations on water management are discussed.

## MATERIALS AND METHODS

### Water Footprint

The WF of a product (commodity, good, or service) is defined as the volume of freshwater that is used for its production. In this study, the water

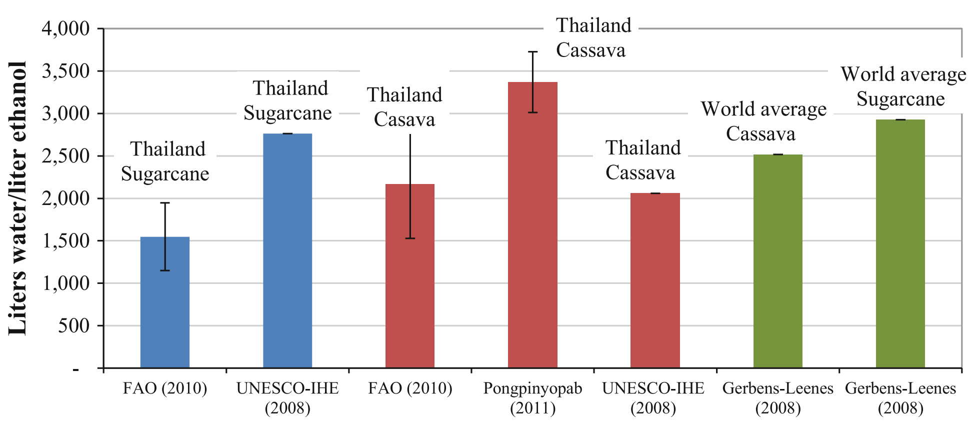


**Figure 1.** WFs of ethanol production (L water/L ethanol) from sugarcane and cassava in Thailand compared to world average.

consumption in ethanol production in Thailand was estimated. To do this, crop cultivation, ethanol plant processes, transportation, and related energy use were all taken into consideration. The WF of crop cultivation in Thailand was also calculated following the 2011 WF assessment manual of Hoekstra et al. (2009). Total water use is a summation of the green water, blue water, and gray water. The green WF refers to rainwater that evaporates during the production process. This is particularly relevant for crop growth. The blue WF refers to surface water and groundwater used for irrigation, which evaporate during production. The gray WF of a product is the volume of polluted water as well as the volume of dilution water that is discharged during the production process; it is defined as the amount of water needed to dilute pollutants emitted to natural water systems during the production process to the extent that the quality of ambient water remains within agreed water quality standards. In this study, green WF was calculated using Thai national data (see ''Crop Cultivation'' section); blue WF and gray WF were verified by field survey data.

## Crop Cultivation

The crop water requirement (CWR) is the water needed for evapotranspiration under ideal growth conditions; it is measured from planting to harvesting. Conditions are ideal when adequate soil water is maintained by rainfall and/or irrigation so that it does not limit plant growth and crop yield. The CWR is calculated by multiplying the reference crop evapotranspiration ($ET_0$) by the crop coefficient ($K_c$): $CWR = K_c \times ET_0$. It is assumed that CWR is fully met so that actual crop $ET_0$ will be equal to CWR: $ET_c = CWR$ (Hoekstra et al. 2009). The $ET_0$ is the evapotranspiration rate from a reference surface. The reference is a hypothetical surface with extensive green grass cover possessing specific characteristics. The only factors affecting $ET_0$ are climatic parameters. $ET_0$ expresses the evaporating power of the atmosphere at a specific location and time of year and does not consider crop characteristics and soil factors. The FAO Penman–Monteith equations were used here to produce the $ET_0$ data reported by the Royal Irrigation Department (2011a). $ET_0$ was calculated using weather data of 120 weather stations within 64 provinces from 1981 to 2010. In this study, $ET_0$ data from the provinces with ethanol plants were selected for our calculations. The $K_c$ varies over the length of a growing period. The value of $K_c$-Penman–Monteith of cassava and sugarcane was obtained from the Royal Irrigation Department (2011b; Irrigation Water Management Research Group) and is summarized in Table 1. According to interviews with farmers, most of them rely solely on green water for crop cultivation; thus, the blue WF in this study was zero. No assessment was made of the gray WF of crops.

Sugarcane and cassava are commonly planted in the northern, northeastern, and central parts of Thailand. The planting time for sugarcane starts in July and ends in December, and the cultivating period is approximately 10–12 months. For cassava, the planting time is from May to July and the cultivating period is about one year. The harvest season for both sugarcane and cassava is from December to February (Office of Agricultural Economics 2010). The interviews with farmers and information from the literature revealed that fertilizer 15-15-15 or 16-16-16 was used on an average 250–313 kg/ha of sugarcane (Department of Agriculture 2012a) or 15-7-18 or 15-15-15 was used on an average 313 kg/ha of cassava (Department of Agriculture 2012b). Diesel use during sugarcane plantation was estimated to be in the range of 94–188 L diesel/ha, while cassava consumed a slightly higher amount at 125–313 L diesel/ha (Thailand Environment Institute Foundation 2007). Since crop yields according to the interviewed farmers varied greatly, the average national crop yield was used for the WF calculations; they are summarized in Table 2.

**Table 1.** Monthly Crop Coefficients ($K_c$) for Sugarcane and Cassava in Thailand

| Month | Sugarcane | Cassava |
|---|---|---|
| January | 0.65 | 0.3 |
| February | 0.86 | 0.3 |
| March | 1.13 | 0.3 |
| April | 1.35 | 0.8 |
| May | 1.56 | 1.1 |
| June | 1.29 | 1.1 |
| July | 1.2 | 1.1 |
| August | 0.93 | 0.5 |
| September | 0.63 | 0.5 |
| October | 0.52 | 0.5 |
| November | | 0.5 |
| December | | 0.5 |

Table 2. Annual Average Crop Yields for Sugarcane and Cassava in Thailand

| | Yield (tons/ha) (Agricultural Information Center 2008, 2010) | | | | |
|---|---|---|---|---|---|
| | 2006 | 2007 | 2008 | 2009 | 2010 |
| Cassava | 21.1 | 22.9 | 21.3 | 22.7 | 18.8 |
| Sugarcane | 49.4 | 63.7 | 69.7 | 69.3 | 68.2 |

Table 3. Economic Values of Sugar Mill Output (Agricultural Information Center 2010; Office of the Cane and Sugar Board 2012)

| | kg | Baht/kg | Allocation |
|---|---|---|---|
| Raw sugar | 60.02 | 8.6–13.2 | 0.23 |
| White sugar | 31.71 | 10.8–17.3 | 0.30 |
| Refined sugar | 16.81 | 21.4 | 0.38 |
| Molasses | 45.42 | 4.87 | 0.09 |

### *Water Use Allocation for the Production of Molasses-Based Ethanol*

Molasses, the input material for ethanol production, is a by-product of sugar mills. For this reason, water consumption during sugarcane plantation and transportation from the field to the sugar mill was allocated by the economic values of the outputs (Thailand Environment Institute Foundation 2007). Sugarcane can be converted to raw sugar, white sugar, refined sugar, and molasses. One ton of sugarcane as an input can produce 45.42 kg of molasses as a by-product. The economic value of molasses is approximately 9% of the outputs (Table 3). The water use in the sugar mill is estimated at 240 L for each ton of sugarcane.

## Ethanol Plant

The water consumptive use of six ethanol plants was collected: two produced molasses-based ethanol, two produced cassava-based ethanol, and two were hybrid ethanol plants. The input materials and production averages are summarized in Table 4. The production was in the range of 100,000–230,000 L/day, accounting for approximately 35% of the current national production. Due to privacy issues, the actual names of the plants have not been disclosed.

## Transportation

Since water is used in the petroleum production process, this study estimated the indirect water use from transportation from the fields to ethanol plants and from ethanol plants to fuel mixing stations. The types of trucks used for loading crop yields and their fuel consumption are summarized in Table 5. The average commute was estimated to be 20–200 km (round trip). Most of the molasses-based ethanol plants in Thailand are located near a sugar mill and the molasses is transported via a pipe using electricity (1.87 kWh/ton-km) (Thailand Environment Institute Foundation 2007).

Normally, between 16,000 and 32,000 L of ethanol is transported by truck from an ethanol plant to a mixing station. The fuel consumption of a 16 K truck is 0.57 L diesel/km-16 K truck and 0.73 L diesel/km-32 K truck. Based on interviews, one round trip was estimated at 150–500 km.

## Petroleum

Since diesel fuel is used during the plantation and transportation processes, the water consumption during petroleum production was counted in the life-cycle process. Wu et al. (2009) reported that the WFs of refined products of conventional USA and Saudi Arabia crude oil were in the range of 3.4–6.6 and 2.8–5.8 L water/L refined products, respectively. About 90% of U.S. onshore oil production consumes from 2.1 to 5.4 L of water for each liter of crude oil recovered. With a consumed average of 1.5 L of water per liter of crude oil refined, a total of 3.6–7.0 L of water is required to produce and process 1 L of crude oil. Similarly, for Saudi Arabian crude oil, 2.9–6.1 L of water is consumed for each liter of crude oil produced and processed.

## Electricity

Estimates of consumptive water use for power generation were obtained from the National Energy Technology Laboratory or NETL (DOE 2009). The NETL (DOE 2009) reported on the water consumption for coal, nuclear, natural gas combined cycle (NGCC), and fossil non-coal (primarily oil-based) power generation, which included the production of primary fuels and water cooling requirements for thermal plants. Figure 2 shows the estimated consumptive water use for the different power plants.

**Table 4.** Daily Average Production in Ethanol Plants in Thailand

| | Plant A | Plant B | Plant C | Plant D | Plant E | Plant F |
|---|---|---|---|---|---|---|
| Input material | Molasses | Molasses | Molasses/cassava | Molasses/cassava | Dry cassava | Fresh/dry cassava |
| Average production (L/day) | 230,000 | 150,000 | 230,000 | 150,000 | 200,000 | 100,000 |

**Table 5.** Truck Fuel Consumption in Thailand

| | Loading (tons/Truck) | Empty Truck (L Diesel/km) (Thailand Environment Institute Foundation 2007) | Full Load (L Diesel/km) (Thailand Environment Institute Foundation 2007) |
|---|---|---|---|
| Tractor trailer | 25–35 | 3–3.50 | 2.50–3 |
| 6-wheel truck | 10–15 | 3.42–3.98 | 2.15–2.97 |
| 10-wheel truck | 18–25 | 2.50–3.50 | 2.28–2.65 |
| Trailer | 32–40 | 4.13–5.97 | 1.70–3.98 |

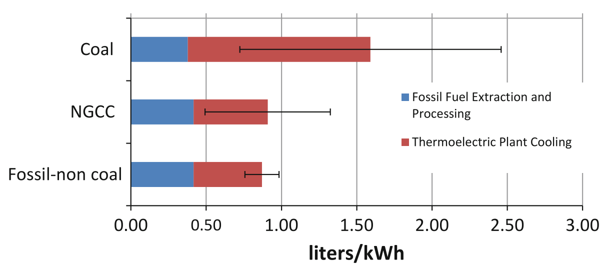


**Figure 2.** Consumptive water use for electricity generation in Thailand.

The uncertainty bars for the thermoelectric plants result from the ranges reported by the NETL. Gleick (1994) reported on the water consumption of hydroelectric-based power generation. Hydroelectric power, on average, requires 17 L of water/kWh, which is largely due to evaporative losses. Differences in evaporative losses result from the weather at, type of, and size of the hydroelectric plant. Seepage losses can also lead to consumptive water use at a hydroelectric power plant.

The Thai national grid mix shows that the majority of power comes from natural gas (68%), followed by coal (24%), hydro-power (7.2%), and fossil fuel (0.8%) (Ministry of Energy 2011). It can thus be estimated that 1.74–2.73 L of water is needed to produce a kilowatt hour of electricity.

## RESULTS AND DISCUSSION

### Water Footprint

The WF of cassava-based ethanol is larger than that of molasses-based ethanol. The WF of ethanol made from molasses was estimated to be in the range of 1,510–1,990 L water/L ethanol, while that made from cassava was 2,300–2,820 L water/L ethanol (Fig. 3). Crop plantation was responsible for approximately 99% of the WF. Water use in the ethanol plant and indirect water use shared a minor portion of the WF. The WF of cassava- and molasses-based ethanol is in the same range as the WF of corn-based ethanol. Research studies reported that corn-based ethanol water consumption (field-to-pump) ranges from 263 to 784 L water/L ethanol (de Fraiture et al. 2008; National Research Council 2008; Pimentel 2003; Pimentel and Patzek 2005) and from 5 to 2,138 L water/L ethanol when including regional irrigation practices (Chiu and Walseth 2009).

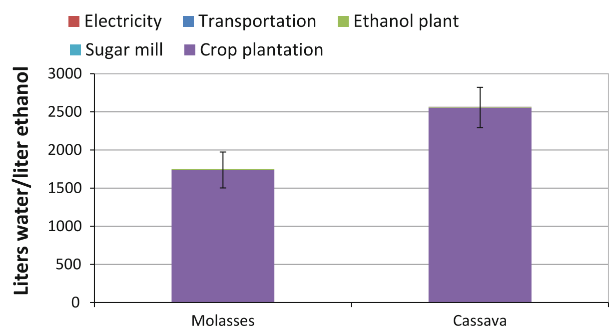


**Figure 3.** WF of ethanol production in Thailand.

#### *Crop Cultivation WF*

The estimated cassava water requirement was in the range of 885–952 mm/year or 8,850–9,519 $m^3$/ha or 415–470 L/kg cassava. Sampattagul and Kongboon (2012) reported that cassava fields in the

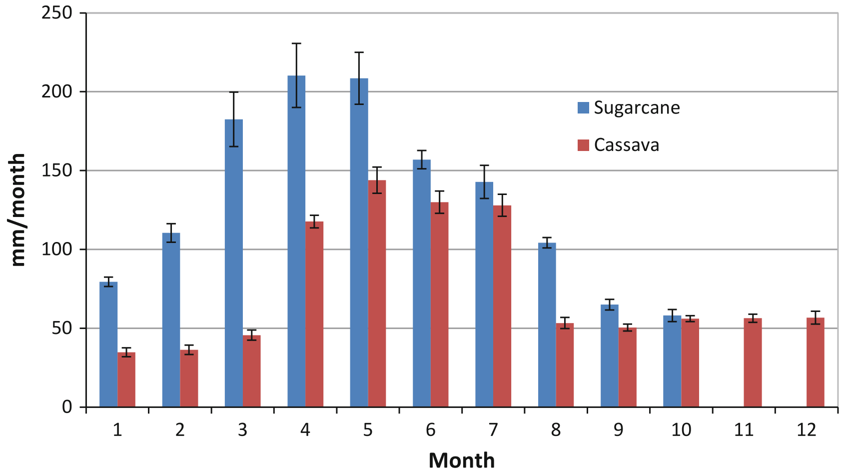


**Figure 4.** CWR of sugarcane and cassava plantations in Thailand.

northern part of Thailand consumed 509 L water/kg (of which 192 was blue water, 232 green water, and 85 gray water). The estimate was slightly higher due to different weather, temperature, and rainfall that affect the $ET_0$.

However, sugarcane requires a larger amount of water than cassava (Fig. 4). CWR tends to peak during summer (April–July). Water requirement for sugarcane was estimated at 1,220–1,400 mm/year or 12,269–14,081 $m^3$/ha or 201–248 L water/kg sugarcane. This estimate is similar to the estimate made by the Royal Irrigation Department (2010); it reported that sugarcane required 172–205 L water/kg. Sampattagul and Kongboon (2012) reported that a kilogram of sugarcane produced in the northern part of Thailand required approximately 202 L water (of which 90 L was blue water, 87 L green water, and 25 L gray water), using the CROPWAT model (FAO 2013).

At a sugar mill, 100–103 kg of sugarcane can produce 3.90–4.25 kg of molasses by-product, which can thus produce 1 L of ethanol. In other words, 1 ha of sugarcane can produce approximately 531–675 L of ethanol per crop cycle. In contrast, approximately 6 kg of fresh cassava or 2.5–2.9 kg of dry-weight cassava can be converted to 1 L of ethanol. In other words, 1 ha can produce 3,138–3,819 L of ethanol.

During crop plantation, indirect water use from fuel consumption was estimated at 0.04–0.15 L water/L ethanol for molasses-based ethanol and 0.11–0.54 L water/L ethanol for cassava-based ethanol. Both organic and chemical fertilizers are normally applied in the field. However, water use during fertilizer production is minimal and can be neglected.

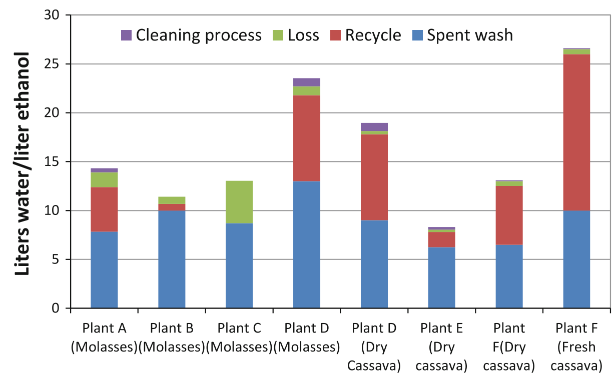


**Figure 5.** Water consumption in ethanol plants in Thailand.

## *Ethanol Plant WF*

The water used in an ethanol plant is usually withdrawn from a river in close proximity to the ethanol plant and stored for future use in reservoirs; this type of water is counted as blue water. Cassava-based ethanol required larger amounts of water than molasses-based ethanol, but the former's actual consumptive water use was less than that of the latter's (Fig. 5). In other words, in an ethanol plant, cassava-based ethanol required larger quantities of water withdrawal. Overall, molasses-based ethanol required 11.42–23.54 L water/L ethanol, dry cassava-based ethanol required 8.30–18.97 L water/L ethanol, and fresh cassava-based ethanol required 26.60 L water/L ethanol. Water used in the boiler, cooling tower, and fresh cassava cleaning process can be reused. The amount of spent wash (i.e., gray water) or Venus from molasses was 7.8–9.9 L/L ethanol, and for cassava it was 5.5–9.7 L/L ethanol. Spent wash is not discarded; instead, it is distributed to farmers since it contains nutritional properties for plant growth. Thailand has a zero wastewater discharge policy; thus, no wastewater is discharged to the natural water systems. Certain plants reported that treated wastewater was used to water trees around ethanol plants.

Indirect water use from fuel and electricity was minor. The sources of energy used in the six studied ethanol plants varied (e.g., the national grid mix, coal, woodchip, biogas, and biomass). The water consumption related to energy in the ethanol plants was 0.22–0.60 L water/L ethanol (molasses-based) and 0.57–0.90 L water/L ethanol (cassava-based).

## WF Affected by Ethanol Policies

As mentioned, the Thai government has announced a renewable energy plan that targets the production of 3M liters ethanol/day in 2008–2011, 6.2M liters/day in 2012–2016, and 9.0M liters/day in 2017–2022. Total water consumption reported as blue water, green water, and gray water is summarized in Table 6.

The average annual rainfall countrywide is 1,700 mm. The total volume of water in all the river basins is estimated at 800 billion $m^3$. Of the total, 600 billion $m^3$ (approximately 75%) is lost through evaporation, evapotranspiration, and infiltration. The remaining 200 billion $m^3$ discharges in rivers and streams (Sethaputra et al. 2001). The agricultural sector is the main user of available water, accounting for 71% of the total water demand; the domestic sector accounts for 5%, the industrial sector accounts for 2%, and the remaining 22% is accounted for by the ecological balance.

With this amount of water availability, water shortage is still the major problem for agricultural sector, especially in the dry season. The problem seems to be more serious since the rapid increase in water demand, while the total water supply remains the same or even decreases due to deforestation (National Science Technology and Innovation Policy Office 2012). In addition, current environment constraints may prohibit large-scale irrigation projects. These would result in more competition for water and point to more serious water shortages in agriculture. With the additional water requirement reported in Table 6, the government must accordingly be prepared for increased water requirements in each region. As mentioned, crop plantation was responsible for approximately 99% of the WF. The agricultural practice in Thailand tremendously relies on rainfall (green water) to grow agricultural products. Fluctuating rainfall, however, causes water excess during the rainy season and water shortage during the dry season. In addition, the irrigation system is only available for certain areas (mostly for paddy fields). The imbalance between rainfall and CWR during the dry season would lead to lower crop yield compared to other countries (as discussed in "Policy Opportunities" section).

**Table 6.** Blue, Green, and Gray Water (M liters/day) in Thailand

| M liters/day | Blue Water | Green Water | Gray Water (Spent Wash) |
|---|---|---|---|
| 3 | 12–25 | 5,213–7,668 | 23–27 |
| 6.2 | 25–52 | 10,774–15,847 | 47–55 |
| 9 | 37–76 | 15,640–23,004 | 68–80 |

Water used in ethanol plants shared a minor portion of the WF, although it is significant in terms of water management since it must be withdrawn from local irrigation systems. In alignment with the ethanol production plan, the government has approved and allowed investors to establish ethanol plants. As of now, the total allowable ethanol production capacity in Thailand is 12.3M liters/day: of this amount, 2.7M liters/day is from molasses-based ethanol plants, 8.6M liters/day is from cassava-based ethanol plants, and 1M liters/day is from hybrid plants. Here are the ethanol production capacity numbers by region: 1.3M liters/day in the northern region, 1.3M liters/day in the central region, 4.2M liters/day in the eastern region, and 5.5M liters/day in the northeastern region. Most of the ethanol plants in the eastern part produce cassava-based ethanol.

If all ethanol plants in Thailand produced at their allowable capacities, their total water consumption (blue water) alone would be 86.6–133.6M liters/day: 10.2–14.2 L in the northern part, 11.3–15.2 L in the central part, 26.0–44.5 L in the eastern part, and 39.1–59.7 L in the northeastern part (the most arid area in the country). This additional water requirement to the existing consumption would definitely introduce water shortage, especially in the northeastern part, if no irrigational system plans to support ethanol production.

**Policy Opportunities**

Freshwater is a fundamental resource for all ecological and societal activities, including food production, industrial activities, and human consumption. One of the biggest water problems in Thailand is water shortage, especially in the dry season. Water supplies in many regions are not sufficient to satisfy all agricultural, industrial, and environmental demands. Obviously, molasses-based ethanol and cassava-based ethanol require significant amounts of fresh water. Without water management plans to preserve the bioethanol supplement in the future, water deficits would be inevitable and would affect crop yields.

The Thai government should acknowledge good farming practices for sustainable crop production and high productivity. According to the FAO (2010a, b), sugarcane yields in Thailand were relatively low compared to other countries, ranking 34th out of 99 countries. Meanwhile, cassava yields ranked Thailand 8th out of 101 countries.

To increase crop yields, additional irrigation and fertilizers must be applied, which will probably lead to greater water use and water pollution. Currently, cassava-based ethanol requires larger amounts of chemical fertilizers than molasses-based ethanol to produce 1 L of ethanol.

For cassava cultivation, farmers apply approximately 313 kg of chemical fertilizer per ha per crop or 87.8 g fertilizer/L ethanol. To cultivate sugarcane, farmers reported using 500–625 kg of chemical fertilizer per ha per crop or 74.1 g fertilizer/L ethanol (molasses).

Biofuel production requires large subsidies. Increasing crop yields (e.g., by improved soil management, irrigation, fertilizer use, and farm machinery) would make ethanol production costs more competitive and, in the long term, could allow for ethanol to be efficiently substituted for gasoline. At present, the Thai government subsidizes ethanol producers to maintain a price that is lower than that of gasoline. The Thai government's exempted oil tax for gasoline mixed with E20 and E85 is 2.58 and 40.65 cents/L ethanol, respectively. In May 2012, the Thai government approved US$5.8 million to compensate cassava-based ethanol producers due to the cassava's price increase. The Thai government not only provided an oil tax exemption for consumers and cost compensation to the ethanol producers but also assured farmers profitable crop prices (Ministry of Energy 2012). Similar to U.S. policy, the Thai government paid 53 cent subsidy for ethanol and cheap corn, driving the increasing corn price due to the demand, while dropping the ethanol price due to the oversupply (Engelhaupt 2007). Since the public is provided these subsidies, the Thai government must insure that promoting biofuel policy is sustainable and does not introduce any risks or damages in the future or entail additional public costs (Ditomaso et al. 2010; Schubert and Blasch 2010).

Uncertainty analysis (e.g., potential greenhouse gas reduction and water consumption) should be incorporated in the decision-making process for future alternative energy policy in Thailand (Mullins and Griffin 2011). Moreover, studies on indirect land-use changes should be included in life-cycle assessment of environmental impacts of biofuels (Lapola et al. 2010; Plevin et al. 2010; Searchinger et al. 2008; Wallington et al. 2012).

Thailand has surplus food capacity. According to the reports (Centre for Agricultural Information 2011; FAO 2011), the most important agricultural export sectors are rice, natural rubber, sugar, and cassava. The domestic consumption of cassava and sugarcane accounted for approximately 27 and 28%, respectively, of the total production. Thus, biofuel production may not affect local food availability, but may affect certain countries like China, Japan, Cambodia, and Indonesia, which are the major importers of the cassava and sugarcane products of Thailand (Centre for Agricultural Information 2011).

WFs of ethanol production should be reduced and should be guided by a water stress index. The water intensity production will need to be decreased in regions of high water stress and increased in regions where water stress is currently low (Ridoutt and Pfister 2010). Molasses-based ethanol seems to be more favorable than cassava-based ethanol in terms of associated water consumption, chemical fertilizer use, and production costs. Since most of the approved ethanol plants in Thailand produce cassava-based ethanol, the Thai government may want to consider promoting molasses-based ethanol production as well as irrigation system improvements and practices to increase crop yields, especially for sugarcane. In addition, the Thai government may want to consider next-generation biofuel in its future energy policy. For example, in the USA, the production of next-generation feedstocks (e.g., municipal solid waste, forest residuals, dedicated energy crops, microalgae) is expected to be better than conventional biofuel production (e.g., corn grain or soybean) when considering these following factors: greenhouse gas emissions, air pollutant emissions, soil health and quality, water use and water quality, wastewater and solid waste streams, and biodiversity and load-use changes (Williams and Inman 2009).

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