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Implications of the biofuels policy mandate in Thailand on water: The case of bioethanol

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HIGHLIGHTS

- The study assesses the implications of Thai bioethanol policy mandate on water.
- Water footprint of cassava, molasses, and sugarcane based ethanol are evaluated.
- Water stress index (WSI) is used to determine the water deprivation potential.
- 1625 Million m^3 of irrigation water/year required to satisfy the ethanol target.
- Two key watersheds in the northeastern of Thailand will face serious water stress.

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ABSTRACT

The study assesses the implications of the bioethanol policy mandate in Thailand of producing 9 M litre ethanol per day by 2021 on water use and water deprivation. The results reveal that water footprint (WF) of bioethanol varies between 1396 and 3105 L water/L ethanol. Cassava ethanol has the highest WF followed by molasses and sugarcane ethanol, respectively. However, in terms of fresh water (especially irrigation water) consumption, molasses ethanol is highest with 699–1220 L/L ethanol. To satisfy the government plan of bioethanol production in 2021, around 1625 million m^3 of irrigation water/year will be additionally required, accounting for about 3% of the current active water storage of Thailand. Two important watersheds in the northeastern region of Thailand are found to be potentially facing serious water stress if water resources are not properly managed. Measures to reduce water footprint of bioethanol are recommended.

1. Introduction

Over the last decades, pressure on freshwater resources is intensifying rapidly due to the growing of agriculture, industrialsation, households and energy consumption especially biofuels which require a huge amount of water for feedstocks cultivation. An assessment of water management in agriculture revealed that a fifth of the world's population or around 1.2 billion people live in areas of physical water scarcity and a further 500 million people are approaching this situation (IWMI, 2007). How to secure the water use in the future therefore has become a global challenge and effective measures in water resources use and management are now required not only local, or national level but also the international level (UNEP, 2011). In addition, the degree of uncertainty in frequency and intensity of flood and drought-affected areas are likely to increase as the result of climate change.

To mitigate climate change, over the past decade, biofuels have been promoted worldwide as the alternative fuels for transport to substitute fossil gasoline and diesel. This has resulted in the continuous increase globally of both bioethanol and biodiesel production from 49,540 and 10,505 M litres in 2007 to 86,986 and 21,463 M litres in 2012, respectively (Earth Policy Institute, 2012). Moreover, the global bioethanol production is almost four times that of biodiesel. The US and Brazil produce 87% of the world's ethanol. Although there are a variety of feedstocks that can be used to produce bioethanol, for commercial ethanol fuel production, the main feedstocks are sugarcane, corn and cassava. For example, the vast majority of U.S. ethanol is produced from corn; meanwhile, Brazil primarily uses sugarcane. The demands

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for biofuels are likely to continue growing due the policy targets of many countries. For example, the Renewable Fuel Standard (RFS) of the US envisions the total amount of biofuel to increase to 136 billion litres by 2022. The Renewable Energy Directive (RED) of EU has specified a 10% renewable content by 2020. Besides the US and EU, 13 countries in the Americas, 12 in Asia-Pacific and 8 in Africa have mandates or targets on biofuels development place (Biofueldigest, 2012).

The biofuel policy mandates worldwide have raised concerns about freshwater resources associated with biofuel feedstocks production which is expected to increase significantly because, in fact, the agriculture already represents 86% of the global water use (Hoekstra and Chapagain, 2007). The large-scale cultivation of biofuel crops would modify the future water demand of agriculture and bring about water competition for food and fuels that need to be assessed especially in some countries that already have the stressed water situation (Berndes, 2002; Gheewala et al., 2011). Moreover, the water consumption and agrochemical use during in the life cycle of biofuel production could also induce adverse impacts on the availability and quality of a precious resource (Dominguez-Faus et al., 2009; Liang et al., 2012). This leads the water aspect to become one of the challenges of sustainable biofuels production as elaborated in many sustainability standards/schemes e.g. Global Bioenergy Partnership (GBEP), Roundtable on Sustainable Biofuels (RSB).

The Thai government has promoted the use of alternative energy as a national agenda since 2004 especially bioethanol derived from the local feedstocks such as molasses, cassava, and sugarcane. The promotion of government has spurred bioethanol production in Thailand from 0.3 M litre/day in 2006 to 1.3 M litre/day in 2011 (DEDE, 2012). This growth is inclined to continue as per the ambitious goal of the recent "Alternative Energy Development Plan: AEDP 2012–2021" which set to produce 9 M litre ethanol/day by 2021. However, the proliferation of bioethanol production promises to increase stress on water and pressure on water resources beyond the natural restoration capacity as agriculture currently consumes 73% of active freshwater storage in the country. This is of particular concern because Thailand has a large agricultural base both for food for local consumption and export as well as for feed and fuel. Some studies have estimated the volumetric water use for ethanol production in Thailand (Kongboon and Sampattagul, 2012; Damen, 2010). However, they have not included the information on water availability and stress which is important for understanding the level of impact on water resources.

The study therefore aims to assess the sustainability implications of the bioethanol policy mandate in Thailand on water. Water requirements for cassava, molasses, and sugarcane based ethanol production in various provinces where bioethanol plants are located are evaluated using the water footprint (WF) concept (Hoekstra et al., 2011) and expressed in terms of sources i.e. green and blue water. Also, the environmental impacts of freshwater use for bioethanol production in life cycle assessment (LCA) are assessed in terms of the water deprivation potential (Pfister et al., 2009) using the Water Stress Index (WSI) developed specifically for the 25 main watersheds in Thailand. The integration of both WF and water stress index approaches is expected to help policy makers especially the Royal Irrigation Department (RID) of Thailand to understand the impacts of bioethanol production on water use and stress and support them to develop measures to minimize water use and to manage the water resources effectively.

2. Bioethanol production in Thailand

As of December 2012, there are 19 ethanol plants in operation with total production capacity of 3.07 M litre/day. This consists of 13 molasses ethanol (MoE) plants (with a total capacity of 2 M litre/day), 5 cassava ethanol (CE) plants (0.78 M litre/day) and a sugarcane ethanol (SCE) plant (0.2 M litre/day). The number of ethanol plants in operation is likely to increase in recent years as nowadays several new plants are under construction, especially cassava ethanol plants (Preechajarn and Prasertsri, 2012). Meanwhile, 48 ethanol plants are registered with the government with a total production capacity of about 12.5 M litre/day consisting of 15 MoE plants, 1 SCE plant, 24 CE plants, and 8 multi-feedstocks ethanol (MoE/CE) plants as summarized in Table 1. Those 48 plants are located/will be located nationwide especially in the North and the Northeastern regions of Thailand where the sugarcane and cassava are widely grown. The locations of the 48 ethanol plants in Thailand classified by provinces and watersheds have been provided in the supporting information (SI) of the manuscript. Around 26 provinces and 11 watersheds in Thailand are directly related to the ethanol production.

3. Methodology

3.1. Water footprint calculation

The concept of water footprint has been introduced as a quantitative indicator of freshwater used for producing a good, or a service. It is the sum of all water consumed including both direct and indirect water consumed in the various stages of production and supply chain (Hoekstra et al., 2011). The WF results are generally evaluated and expressed in terms of sources i.e. green, blue and grey water. Green water represents rainfall consumed through crop evapotranspiration; while, blue water is appropriated from surface and groundwater resources (Ridoutt and Pfister, 2010). Grey water represents to the theoretical volume of water needed to dilute pollutants discharged to water bodies to the extent that they do not exceed minimum regulatory standards (Hoekstra et al., 2011). Nowadays, it is recognized as a tool to raise awareness on water resources and to support policy makers in improvement of water resource management (Chapagain and Hoekstra, 2008). Over the past decades, water footprint has been used to calculate the water use for a wide range of products especially crops and agri-food products products (Chapagain and Hoekstra, 2008; Siebert and Döll, 2010), and also biofuel crops and biofuels (Gerbens-Leenes et al., 2009; Damen, 2010). Nevertheless, there is a considerable variability and uncertainty in the results of a crop's water footprint (WF) depending on many factors such as geographical and climatic conditions of the studied areas, crops varieties and cultivation practices (Scown et al., 2011; Marta et al., 2012; Guieysse et al., 2013). Therefore, the specific assessment of WF of bioethanol crops grown in different regions of Thailand is necessary.

In the study, the water footprint concept is used to determine and compare the water requirements for three major bioethanol products in Thailand i.e. ethanol from molasses, cassava and sugarcane. The studied bioethanol production systems can be divided into three main stages including (1) feedstocks cultivation i.e. cultivation of sugarcane and cassava, (2) feedstocks processing i.e. sugar milling and molasses production, and (3) ethanol conversion.

Table 1
Ethanol plants in Thailand.

Ethanol plants classified by feedstock	Licensed plants		Plants in operation	
	Number of plants	Capacity (M litre/day)	Number of plants	Capacity (M litre/day)
Molasses	15	2.685	5	0.78
Sugarcane juice	1	0.2	1	0.2
Molasses/cassava	8	1.22	8	1.22
Cassava	24	8.39	5	0.78
Total	48	12.495	19	3.07

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The unit of comparison for the water footprint assessment is a litre of bioethanol (99.5% purity). The study focuses on the direct consumptive water use for those three main stages of bioethanol production, especially the irrigation water required for cultivating crops for bioethanol which is the important water use type from the view point of water resources management. Essentially, the irrigation water required for the dry season may lead to acute water shortage and water competition with other users. The indirect water consumption e.g. the amount of water required for producing energy carriers, materials or chemicals supplied to the bioethanol system is excluded from the system boundary of the study as they are not significant as compared to irrigation water required for crops (Scown et al., 2011) and they are also not the focus for the target audience of the study i.e. RID whose mission is to manage the irrigation water resources of the country especially for agriculture. In fact, the indirect water consumption may not even be part of the same watershed as it can occur in a different location where the energy carriers or materials are produced. Grey water was also not considered in the study as the impacts of wastewater generated from bioethanol production system have already been evaluated in the terms of eutrophication and eco-toxicity in several studies (Silalertruksa and Gheewala, 2009). The details of methodologies, assumptions used, and data sources for calculating water requirements in each stage are described below.

3.1.1. Water requirements for bioethanol crops cultivation

In the study, the "consumptive water use" or "crop water requirement" over the period of sugarcane and cassava cultivation in 26 provinces of Thailand where ethanol plants are located is quantified. The general formula is as follows: $ET_{crop} = K_c \times ET_o$ [Unit: mm/day]; where ET = crop evapotranspiration i.e. the amount of water evapotranspired by the crops in a specific climate regime and adequate soil water is maintained by rainfall and/or irrigation (Allen et al., 1998); K_c = Crop coefficient of Penman-Monteith; and ET_o = the reference crop evapotranspiration of Penman Monteith (Allen et al., 1998). Data sources for calculation are shown in the SI of the manuscript.

As the planting period generally differs from region to region, the sugarcane and cassava calendars of the OAE are referred in the assessment. Sugarcane is generally planted in the beginning of rainy season and is harvested within 10–12 months after plantation i.e. around November–May. On the other hand, cassava can, in principle, be planted all year round. Nevertheless, about two thirds of the cassava is planted at the beginning of the rainy season i.e. March–May (Suksri et al., 2007). Only around 20% of cassava is planted in the dry season i.e. November–February and the remaining planted between June and October. Cassava is generally harvested within 10–12 months after plantation and the period that cassava is most harvested is January and February (Suksri et al., 2007).

Blue water footprint (BW) and green water footprint (GW) are also categorized in the study. Blue water refers to the water withdrawn from surface or underground, and it particularly implies to the irrigation water requirements in the case of agricultural production. Generally, BW has been attached more significance than green water (i.e. precipitation and soil moisture consumed on-site by vegetation) as it has more economic value especially for the dry season.

3.1.2. Water requirements for feedstock processing

For the case of molasses based ethanol production, the sugar mill is involved as the feedstock processing step to produce molasses feedstock. Sugar milling involves crushing cane to extract sugarcane juice. This juice is clarified to remove any impurities and concentrated into syrup by boiling off excess water, seeded with raw sugar crystals in a vacuum pan and boiled until sugar crystals have formed and grown (Silalertruksa and Gheewala, 2009). The crystals are separated from the syrup by centrifugal process before more crystals are grown in the syrup. Therefore, a variety of products and wastes will be generated in the mills i.e. sugar is the main product; molasses, the syrup remaining after the sugar has passed through the centrifuge for the last time in a mill or refinery, is a by-product as well as bagasse which is generated after sugarcane crushing and it used to produce steam and electricity to supply for the mills and the surplus electricity is sold to the general grid-mix. The other residues such as filter cake and wastewater effluents from the mills are considered as waste in the study because generally they done not have an economic value and are hence, not traded.

To share the water use from sugarcane cultivation and sugar milling between the sugar (main product) and the by-products i.e. molasses and bagasse, the energy-based allocation techniques is applied in the study. In the mills, a ton of sugarcane processed will generate 109, 45, and 287 kg of sugar, molasses, and bagasse, respectively. However, only the surplus bagasse after internal use in the mills (for own energy requirements) i.e. about 131 kilogram per ton sugarcane, that will be considered in the allocation calculation. Based on the average energy content of sugar, molasses and bagasse of about 16.33, 11.43 and 7.53 MJ/kg respectively (Silalertruksa and Gheewala, 2009), the allocation factors for sugar, molasses and the surplus bagasse are 0.54, 0.16 and 0.30, respectively. The factor of 0.16 is used for determining the water use for molasses production. Based on all processes including sugarcane washing, extraction, juice treatment, juice concentration by condenser and evaporation (excluding ethanol production), the water use is estimated to be around 1.23 m^3 per ton of processed cane (Macedo et al., 2005; Gerbens-Leenes and Hoekstra, 2009). The water use in sugar mills for molasses is estimated to be around 4.37 m^3/ton molasses.

The water use in the industrial processes i.e. feedstock processing and ethanol conversion are considered to contribute to the blue WF. Effluents generated in this process contribute to water pollution. As cassava ethanol is mainly produced from fresh cassava root and also the dried chip processing step does not require the water; therefore, the process of converting fresh cassava to dried chips form is not account in the study.

3.1.3. Water requirements for bioethanol conversion

3.1.3.1. Molasses ethanol. The processes of molasses ethanol production consist of yeast preparation, fermentation, distillation and dehydration. The study refers production data of molasses ethanol conversion from literature (Silalertruksa and Gheewala, 2009; KAPI, 2007). To produce a litre of molasses ethanol, around 4.6 kilogram of molasses is required or equivalent to around 61 L of molasses ethanol/ton of sugarcane (based on the allocation factor for molasses of about 0.16). The water used at the ethanol conversion stage is about 8.6 L L/L of molasses ethanol. It is classified as "blue water" and the two main water-intensive processes are the fermentation and the supporting process as steam generation.

3.1.3.2. Sugarcane ethanol. To produce sugarcane ethanol, sugarcane juice which is extracted from sugarcane crushing process will be directly used to produce ethanol without the production of sugar. Bagasse is used to produce steam and electricity. Blue water required at this stage is about 14.3 L/L sugarcane ethanol and it is mainly for steam production. Spent wash is sent to aerobic ponds with biogas recovery system. To produce a litre of sugarcane ethanol, around 11.6 kilogram of sugarcane is required or equivalent to around 86 L of sugarcane ethanol/ton of sugarcane (Silalertruksa and Gheewala, 2011).

3.1.3.3. Cassava ethanol. The cassava ethanol plant consists of five main processes i.e. (1) cassava preparation including cleaning and milling; (2) liquefaction, (3) fermentation, (4) distillation and (5) molecular sieve dehydration. In this industrial stage, water is used for mixing and liquefaction and for industrial boilers for steam production. Thus, the water used in this stage is mainly classified as "blue water". About 6.2 kilogram cassava root is required to produce a litre ethanol or equivalent to around 161 L cassava ethanol/ton of cassava root. Blue water use for cassava ethanol production is referred from the literature i.e. around 11.1 L/L cassava ethanol (Silalertruksa and Gheewala, 2009; KAPI, 2007).

3.2. Water stress index (WSI) and characterization factors

As the availability and quality of freshwater resources are unevenly distributed and varied by the hydrological processes in each region, a litre of water used in the already stressed areas is therefore likely to cause more damage than a litre consumed in more water-rich areas (Scown et al., 2011). Hence, comparing the water footprint of biofuels individually will not be able to reveal the real burdens of water use if local levels of water stress are not taken into account (Jeswani and Azapagic, 2011). To reveal the competitive pressure on water resources availability in a specific region, the study applied the water stress index (WSI) approach of Pfister et al. (2009) for the characterization factors to translate the impact of water use for bioethanol production in Thailand. The levels of water stress are designated into 5 levels including extreme, severe, stress, moderate and low.

Water stress is commonly defined as the ratio of total annual freshwater withdrawals to hydrological availability (WTA). Moderate and severe water stress occur if WTA is above a threshold of 20% and 40%, respectively (Vörösmarty et al., 2000). However, with Pfister's approach, WSI is adjusted to range between 0 and 1 in order to serve as a characterization factor for "water deprivation" (Pfister et al., 2009). For Thailand, the office of the national water resources committee has divided the country into 25 watersheds covering the catchment areas of about 511, 362 km^2 for hydrological purposes. Therefore, the local water stress index (WSI) for those 25 watersheds have been quantified by JGSEE (2013) and is referred to as the characterization factors for determining the impact of water use or so called "water deprivation". The steps to evaluate WSI index are as follows: (1) Determining the ratio of total water withdrawals to hydrological availability of a basin, termed as "Withdrawal-to-Availability (WTA)", of the 25 individual watersheds of Thailand by using the annual water demand and annual water availability data from RID; (2) Determining the "weighted WTA" for each watershed by considering on the variations in monthly or annual rainfall as well as the factors regarding the regulated flow of the watershed; and (3) Determining the WSI.

The WSI for each watershed is used as the characterization factor for calculating the "water deprivation" impact. The water deprivation impact potential can be calculated from the multiplication of blue water with the water stress index (WSI) in the specific location: Water deprivation = Blue water × WSI. This water deprivation potential, so called the "RED (Relevant for Environmental Deficiency) water", is measured in m^3 water equivalents (m^3eq) and represents a surrogate indicator for the amount of water deficiency to downstream human users and ecosystems (Pfister et al., 2009).

4. Results and discussion

4.1. Water footprint of bioethanol production in Thailand

4.1.1. Comparative WF of the bioethanol feedstocks

Fig. 1 shows the comparison of water footprint per ton of bioethanol feedstock in Thailand including cassava, sugarcane and molasses. Based on the 26 studied provinces, the total WF for cassava, sugarcane and molasses range between 381–456, 119–188 and 428–673 m^3/t, respectively. The large variation of WF results among the provinces is due to the factors such as geographic and climatic variables in each province, cultivation calendar, and the variation in yields.

For irrigation water requirement which is expressed by blue WF, the results show that although both cassava and sugarcane in Thailand are mainly rainfed crops, rain water contributing about 80% and 71% of the total WF. The irrigation water required to produce a ton of cassava, sugarcane, and molasses ranges between 47–160, 21–77, and 79–278 m^3, respectively.

4.1.2. Comparative WF of bioethanol

The water footprint of bioethanol in Thailand varies between 1396 and 3105 L/L ethanol as shown in Table 2. Based on the average WF values, cassava ethanol uses the highest amount of water followed by molasses ethanol and sugarcane ethanol, respectively. Nevertheless, there is the wide range in the results due to the variation in geographic and climatic conditions and also the variation in yields of feedstocks. For example, the WF of cassava ethanol can vary between 2374 and 2841 L/L ethanol; while, the ranges of WF of sugarcane and molasses ethanol are 1396–2196 and 1976–3105 litre, respectively. The lowest WF for cassava ethanol would be in Kalasin province; meanwhile, that for sugarcane ethanol would be in Suphanburi. On the contrary, the highest WF for cassava ethanol would be in Sa Kaeo province; meanwhile, that for sugarcane ethanol would be in Chonburi. However, in terms of the blue water use, cassava uses much less than molasses and sugarcane for bioethanol production. Producing molasses ethanol requires the highest amount of blue water i.e. around 699–1220 L of blue water/L ethanol; meanwhile, cassava ethanol and sugarcane ethanol consume around 449–566 and 450–859 L of blue water/L ethanol, respectively.

The contributions of blue water consumed in the various life cycle stages of molasses, sugarcane and cassava ethanol production are shown in Fig. 2. The agricultural stage i.e. feedstock cultivation is the major contributor to the blue water consumption by sharing around 97–98% of the total blue water use. While, the industrial stages such as sugar milling and ethanol conversions contribute just about 2–3% of the total blue water consumption. At the sugar milling stage which is the origin of molasses feedstock, sugarcane washing and sugarcane juice evaporation in a multiple-effect evaporator before further concentrating to become sugar and molasses, are the two major freshwater intensive processes. While, in case of sugarcane ethanol production, the ethanol plant is supposed to be attached to the sugar mill and the total blue water consumed since sugarcane washing until distillation of ethanol is estimated to be about 14.3 litre/litre ethanol. For ethanol conversion stage, conversion of cassava to ethanol will require much amount of blue water as compared to conversions of molasses and sugarcane to ethanol. For cassava ethanol, blue water was highly consumed in the mixing and liquefaction processes to convert starch to sugar before fermentation and distillation of ethanol.

4.2. Water deprivation impact potentials from bioethanol production in Thailand

The water stress index (WSI) of 25 major watersheds of Thailand are evaluated and applied as the characterization factors to determine the water deprivation potential i.e. the amount of water deficient to downstream human users and ecosystems (Pfister et al., 2009), from water consumption of bioethanol production. To calculate this indicator, blue water consumption for bioethanol production in a specific region will be multiplied with the WSI of that region and measured in m^3 water-equivalents (m^3eq). The

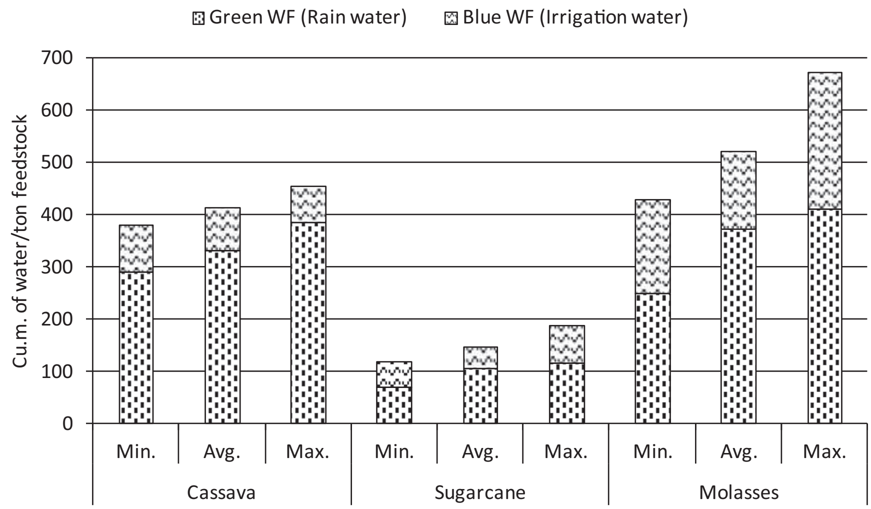

Fig. 1. WF of major bioethanol feedstocks in Thailand.

Table 2
WF of cassava, sugarcane and molasses bioethanol production in Thailand.

	Water footprint (L water/L bioethanol)		
	Green WF	Blue WF	Total WF
Cassava ethanol			
Min.	1806	566	2372
Avg.	2051	528	2582
Max.	2389	449	2838
Sugarcane ethanol			
Min.	814	582	1396
Avg.	1218	490	1708
Max.	1337	859	2196
Molasses ethanol			
Min.	1147	829	1976
Avg.	1711	699	2410
Max.	1885	1220	3105

WSI for 25 major watersheds of Thailand has been studied by JGSEE (2013). The results show that the WSI values in Thailand vary in a wide range from 0.012 for Peninsular-West coast basin to 0.927 for the Mun basin (JGSEE, 2013). There are four watersheds that can be categorized as extreme and severe water stress based on their existing water withdrawal and availability ratios. The watershed with the most severe water stress is the Mun basin, followed by Chi, Chao Phraya and Thachin, respectively. Therefore, those four watersheds have the high potential on water deprivation to the other users. Based on the bioethanol promotion, there are around 26 provinces and 13 major watersheds that would be directly associated with the bioethanol production in the future including the high water stress regions like the Mun, Chi, Chao Phraya and Thachin watersheds.

Table 3 shows the water deprivation potentials from consumptive water use to produce a litre of bioethanol in the different provinces and watersheds that the ethanol plants located. The results reveal that the water deprivation indicator can help to screen and prioritize the areas that potentially face the water competition which cannot reveal by the WF values. For example, cassava and cassava ethanol produced from the watersheds e.g. Mun, Chi and Chaophraya will result in the water deprivation impact greater than cassava and cassava ethanol produced in the other watersheds. Therefore, the policy makers should have the measures to supporting the increased water use for bioethanol production in those regions in the future.

Nevertheless, it must be noted that the consumptive water use for bioethanol feedstocks shown in Tables 2 and 3 are the

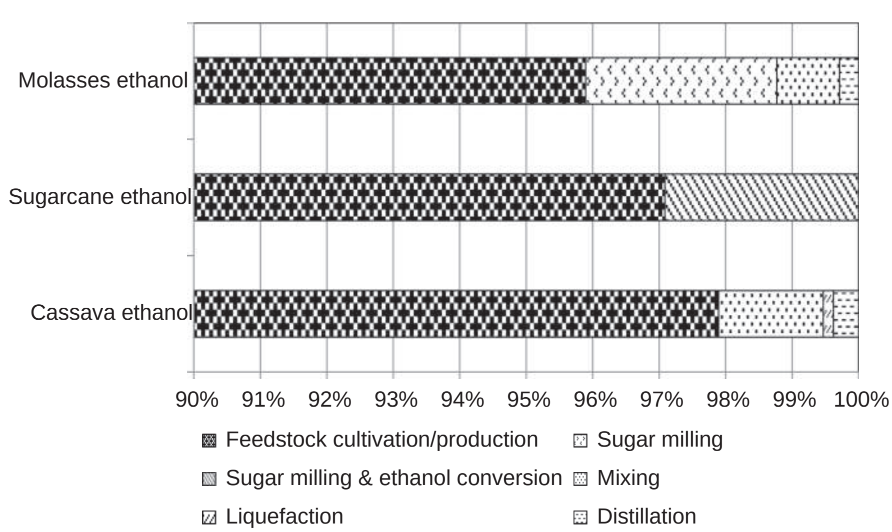

Fig. 2. Blue water use classified by various processes in the life cycle of bioethanol production.

Table 3
Water deprivation potentials of bioethanol production in Thailand.

Related watersheds	Provinces	Water deprivation impact potentials (m^3 eq./L ethanol)		
		Cassava ethanol	Sugarcane ethanol	Molasses ethanol
Mun	Nakhonratchasima, Buriram, Ubon Ratchathani	442–548		468–591
Chi	Kalasin, Khon Kaen, Chaiyaphum, Nongbualumphu	267–320		279–337
Chao Phraya	Nakhonsawan, Lopburi, Ayutthaya	266		162–367
Thachin	Nakhonpathom, Suphanburi			224–235
Bang Pakong	Chachoengsao	8		
East Coast Gulf	Chonburi, Rayong	5–8		18
Khong	Mukdahan, Udon Thani	6		9
Mae Klong	Kanchanaburi, Ratchaburi	7–18		9–23
Pasak	Phetchabun, Saraburi			18–31
Ping	Kamphaengphet	8		10
Prachinburi	Prachinburi, Sa Kaeo	6–7		9
Sakae Krang	Uthai Thani	18		
Salawin	Tak		6	8

theoretical water consumption which will result in the overestimation for the cultivations that are subject to deficit irrigation (Pfister et al., 2009). This is especially for the cassava and sugarcane in Thailand which are rainfed crops. However, to estimate the irrigation water consumed by field crops like sugarcane and cassava in reality is difficult as it depends on not only whether the plantation areas are located in the irrigation areas, but also depends on how much the irrigation water available in each year depending on the climatic variables. Anyway, for the rough estimation of irrigation water actually used by sugarcane and cassava, the study refers to the water resources management plan for agricultural plantation in irrigated areas during dry season of year 2011/2011 (RID, 2012), the report shows that there are around 0.22 M ha of total field crops planted areas that will be able to receive the irrigation water from RID and around 0.16 M ha is the sugarcane planted areas. This irrigated sugarcane plantation areas will account for only 13% of the total sugarcane planted areas in Thailand which it is about 1.24 M ha. Based on the average yields of sugarcane which is around 72 ton/ha, the actual blue water footprint of sugarcane in Thailand would be only 5 m^3/ton sugarcane which quite different from the theoretical blue water value shown in Fig. 1 which is 41 m^3/ton sugarcane. This brings about a drastic reduction in blue WF per litre of sugarcane ethanol from 490 to 72 L water/L sugarcane ethanol. Nevertheless, the calculation above is based on the official irrigated areas reported by RID; but farmers outside the official irrigated areas also use water supplied from other sources for their plantations. However at present, there are no official irrigated areas of cassava plantation in Thailand (Damen, 2010).

4.3. Implications of the bioethanol policy mandate on water use and stress

The study assesses the potential impacts on water use and water stress with respect to the policy mandate of bioethanol production in Thailand. Two scenarios are developed including:

4.3.1. Scenario 1: policy mandate scenario

The scenario assumes that the AEDP's target of producing 9 M litre ethanol/day by 2021 will be satisfied by the 48 licensed ethanol plants. The scenarios assume that only molasses, cassava and sugarcane juice are the feedstocks. All 48 ethanol plants licensed by the government can start operation in accordance with the proposed schedule and the ratios of feedstocks used for the 8 multi-feedstocks bioethanol plants are assumed on a 50/50 basis by sharing between the molasses and cassava. To satisfy the target of 9 M litre ethanol/day, the ethanol plants are assumed to operate at 72% of their production capacities;

4.3.2. Scenario 2: full production capacity scenario

The scenario assumes that all 48 plants will be operated at the full production capacity i.e. 12.495 M litre ethanol/day. Thus, production of 4560 M litre ethanol/year would be the mandated bioethanol target of this scenario. The future changes in yields of cassava and sugarcane per hectare are neglected in the assessment as there are many factors e.g. climatic conditions, agricultural practices, future varieties development involved to the variation of crops' yields.

The results show that, to satisfy the AEDP bioethanol target in year 2021, around 8185 million m^3/year are required with 6560 million m^3 rain water (80%) and 1625 million m^3 irrigation water as shown in Table 4. In addition, if the ethanol plants were fully operated as per the scenario 2, the demand of irrigation water to fulfill the ethanol production would be increased to 2256 million m^3 in 2021. The blue water requirements for scenarios 1 and 2 are equivalent to about 3% and 4% of the active water storage of Thailand in year 2012 which is around 55,268 million m^3. About 60% of the total blue water requirements i.e. 958 million m^3 is for cassava ethanol production.

Fig. 3 shows the classification of 1625 million m^3 blue water required in 2021 to satisfy the AEDP's target of bioethanol production by watersheds. Mun, Chi and Prachinburi are the three important watersheds that would have the significant increase in irrigation water demand for bioethanol production. Considering the water deprivation potentials (m^3 eq/year), Mun, and Chi would be the two main watersheds that have high potential to confront the pressures on water stress and competition with other users if the water resources were not properly managed in the future (as Fig. 3). Importantly, both watersheds are in the Northeastern region of Thailand which has the largest crops plantation areas in Thailand. By provinces, there are three provinces that potentially have the high impact on water use due to the ethanol policy mandate i.e. Nakhonratchasima, Ubon Ratchathani and Chaiyaphum, as they would have several new ethanol plants established there and from the hydrological perspective, those three provinces are under the Mun and Chi watersheds.

4.4. Recommendations to enhance water efficiency of bioethanol production in Thailand

For the sustainability of large scale bioethanol production in Thailand due to the policy mandate, it is necessary to enhance water resource management and efficiency across the entire life cycle of bioethanol production to avoid the pressure on water competition. Several measures are recommended as follows:

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Table 4
Estimated water requirements for future bioethanol production in Thailand.

		Water requirements (million m^3/year)					
		Dry season		Wet season		Total	
		Green water	Blue water	Green water	Blue water	Green water	Blue water
Scenario 1: policy mandate scenario	Cassava ethanol plants	754	933	3974	25	4728	958
	Sugarcane ethanol plants	8	17	75	1	83	18
	Molasses ethanol plants	102	295	1039	159	1141	454
	Multi-feedstocks plants	74	146	534	49	608	195
	Total	938	1391	5622	222	6560	1624
Scenario 2: full production capacity scenario	Cassava ethanol plants	1047	1296	5520	34	6567	1331
	Sugarcane ethanol plants	11	23	104	2	115	25
	Molasses ethanol plants	141	410	1444	220	1585	630
	Multi-feedstocks plants	103	203	741	68	844	270
	Total	1303	1932	7809	324	9112	2256

4.4.1. Crop evapotranspiration (ET) reduction

Crop evapotranspiration (ET) during the bioethanol feedstock cultivation stage contributes more than 99% of the total WF of bioethanol or around 95–98% of the total blue water footprint of bioethanol. Therefore, in the water supply perspective, the ideal fuel crops to minimize the water footprint of biofuels should be drought-tolerant, high-yield crops grown on little irrigation water (Domiguez-Faus et al., 2009). There are many factors that able to influence the evapotranspriration of crops e.g. temperature, crop yields, crop cycle and agricultural practices. For example, ET generally increases with the temperature. To reduce the crop evapotranspiration, shortening of the crop cycle or else improving crop yields are the possible methods. However, those two methods generally must be traded off with each other as shortening the crop cycle may result in lower biomass accumulation which in turn will decrease the final yields. Therefore, the development of more efficient crop varieties is important to the sustainability of large scale bioethanol production in the future.

For Thailand, the country average yields of cassava and sugarcane in 2011 are 19.3 and 76.2 tons/ha, respectively (OAE, 2012). The lowest yields are found in the Northeastern region of Thailand which has the large cultivation areas associated with the Mun and Chi watersheds i.e. around 19.2 tons cassava/ha and 74.4 tons sugarcane/ha (OAE, 2012). However, due to the continual development of high yield varieties, the varieties of cassava such as Rayong 5, Rayong 9, Rayong 72 and Kasetsart 50 and the sugarcane varieties such as K 84-200, K 90-54 and U thong 3 are being recommended to Thai farmers which potentially yield about 31–50 ton/ha for cassava and 94–112 ton/ha for sugarcane. Nevertheless, to achieve the high genetic potential yields, those high yields must be supported with good agricultural practices in farming e.g. improving soil quality by using organic fertilizers and good practices in land preparation, plantation, harvesting and regularly weed control (Silalertruksa and Gheewala, 2009). In addition, more efficient irrigation systems are also required in the high potential water stress regions caused by the large scale bioethanol. The study revealed that the Mun and Chi are the two watersheds that the government agencies should attach significance.

4.4.2. Promotion of sugarcane ethanol into the Thai bioethanol system

As the results show that ethanol derived from sugarcane juice has the lowest total WF and also the blue water footprint required

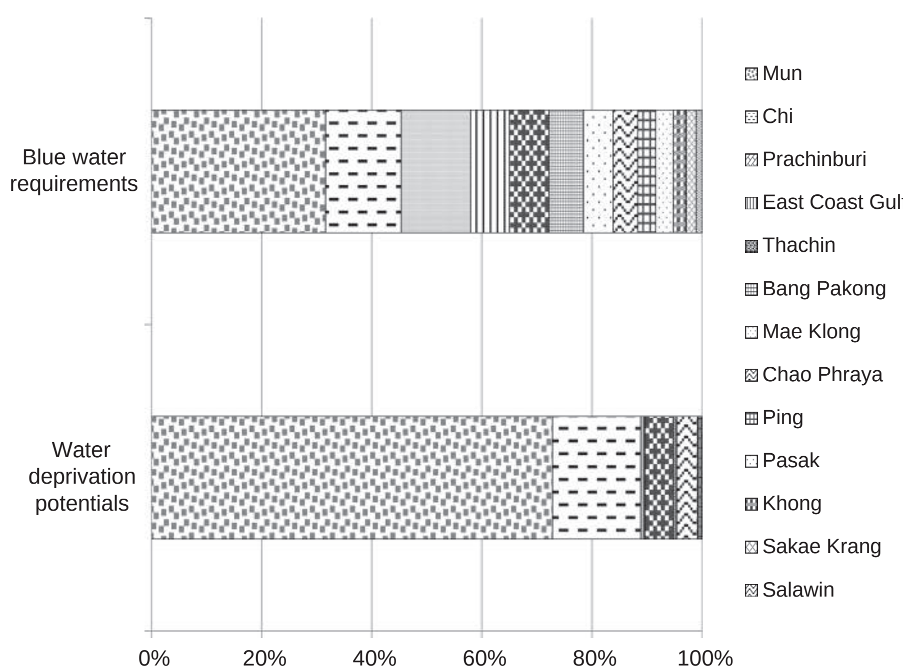

Fig. 3. Blue water requirements and water deprivation potentials from bioethanol production in 2021 classified by watersheds.

as compared to cassava and molasses ethanol, the substitution of cassava ethanol and molasses ethanol by sugarcane juice ethanol can help reduce the blue water requirements by around 38 and 209 litre of blue water/litre ethanol, respectively. In addition, sugarcane is found as the crucial feedstock that can increase the security of feedstocks supply for bioethanol production in Thailand and its performance in GHG emissions is better than cassava and molasses ethanol (Silalertruksa and Gheewala, 2011). Nevertheless, based on the registered ethanol plants, there is only one ethanol plant using sugarcane juice as feedstock in operation in Thailand (0.2 M liter ethanol production capacity per day). The government therefore should emphasize promotion of sugarcane juice ethanol production by solving some of the existing constraints such as the Sugar Act of 1984 which does not support ethanol production from sugarcane. Under the Sugar Act, cane growers receive a 70% share of revenue from sugar and molasses sales after deducting all costs and taxes, and mills receive the remaining 30%. Therefore, if the sugar mills utilize sugarcane juice to produce ethanol directly, the revenue-sharing system may need to be adjusted and this question is still a controversial issue among various stakeholders. In addition, the duration of sugarcane supply is limited to just over the period of December–March.

4.4.3. Promotion of second generation biofuels

Another important way to mitigate the water competition in the future due to the bioethanol target in Thailand and the increasing demands for both sugarcane and cassava for food and other purposes could be via the promotion and development of second generation biofuels. It is likely that within the next ten years, conversion of lignocellulosic materials to biofuels will have reached a stage that these become the primary and preferred feedstock for biofuel production, in particular bioethanol (Gheewala et al., 2011). Agricultural residues such as rice straw, cane trash, and oil palm residues which are currently being burnt in the open-fields causing air pollution problems could be appropriate feedstocks to consider.

4.4.4. Enhancing water use efficiency in feedstock processing and ethanol conversion

Although, feedstock processing and ethanol conversion have the very low contributions to the WF of bioethanol as compared to the crop evapotranspiration, those industrial processes directly involve blue water use which is recognized as the important element of WF as it is more associated with the environmental impacts as compared to the green water. To reduce the WF during industrial stages, the water reuse and recycle program has to be encouraged. For example, the condensate recovery in sugar mills and in ethanol conversion plant e.g. distillation stage can help not only saving the water use but also help saving energy. Brazil has accelerated the basic guidelines of water management to sugar milling industries along with the new technologies development such as dry cleaning of sugar cane to eliminate sugarcane washing, treatment of vinasse by biodigestion technique to reduce the organic load and recirculating into the process (Macedo, 2005; Macedo et al., 2008). Moreover, the appropriate treatment and utilization of the high organic wastewater generated from the mills and from the ethanol conversions such as using it as agri-fertilizer can help mitigate impacts on ecosystem due to wastewater release. Therefore, research and development for the feedstock processing technologies and ethanol conversion technologies need to be encouraged.

5. Conclusions

The promotion of bioethanol in Thailand raises concerns on the possibility of increased stress on water vis-à-vis competition for food, feed and fuel. The water footprint of bioethanol in Thailand varies between 1396–3105 L water/L ethanol with cassava ethanol the highest followed by molasses and sugarcane ethanol. However, in terms of blue water consumption, molasses is the highest followed by cassava and sugarcane. To satisfy the bioethanol target in 2021, two watersheds in Northeast Thailand would have a significant increase in irrigation water demand that could potentially lead to pressures on water stress. Several measures are recommended to address this.

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