Sustainability **2011**, *3*, 518-530; doi:10.3390/su3030518

OPEN ACCESS

sustainability

ISSN 2071-1050

www.mdpi.com/journal/sustainability

Article

Sustainability Assessment of a Biorefinery Complex in Thailand

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Received: 1 February 2011; in revised form: 16 February 2011 / Accepted: 28 February 2011 / Published: 21 March 2011

Abstract: In this paper, a biorefinery complex in Thailand was assessed *vis-à-vis* sustainability. The complex studied includes plantations of sugarcane and a biorefinery system composed of several units including, a sugar mill, power plant, ethanol factory and fertilizer plant. The assessment aimed at evaluating the environmental and socio-economic implications relating to molasses-based ethanol production and use, and maximized utilization of the biomass materials produced as part of the biorefinery complex. Global warming potential, human development index and total value added are the three indicators that were selected to perform the assessment. The results obtained revealed that the maximization of biomass utilization at the level of the biorefinery complex provide greenhouse gases emissions reduction benefits, enhanced living conditions for sugarcane farmers and employees of the biorefinery, and economic benefits, particularly with regard to profit and income generation. These results could serve as a first step to further improve and design indicators for sustainability assessment of biomass utilization.

Keywords: sustainability; biorefinery; Thailand

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1. Introduction

The utilization of biomass for energy is being promoted worldwide as a means to provide national energy security benefits to countries relying on fossil fuel energy imports. They also provide, under certain conditions of cultivation and production, environmental benefits, notably with regard to greenhouse gas (GHG) emissions reductions. However, issues of land use change, biodiversity loss, and water consumption are among some of the challenges reported in the literature to potentially contribute to reducing the benefits of biomass based energy [1-3].

As one type of bioenergy, liquid transportation fuels or biofuels are particularly promoted in countries rich in biomass resources. In Thailand, bio-ethanol production and use has been encouraged by the government for several years. This is not only to reduce oil importation and contribute to global warming mitigation but also to activate the grassroots economy by stabilizing the income of farmers and generating employment in the local community [4]. Since the approval by the Thai government of a package of incentives in favor of domestic production of bioethanol in 2000 [5], a set of production targets have been set to promote the use of gasohol (ethanol blended with gasoline) in the country. In the latest renewable energy policy plan referred to as the 15 years' alternative energy plan, a target of three million liters ethanol per day by 2011 has been set increasing to nine million liters per day by 2022 [6]. Gasohol was introduced first in the greater Bangkok region in 2005 in the form of a 10% blend with octane 95 gasoline. It is now available nationwide as a 10% blend with octane 91 gasoline. In early 2008, a 20% blend or E20 was launched, which is now available nationwide, while a 85% blend or E85 was introduced in late 2008 and is currently available at some stations in Bangkok [2,7].

Currently, cane molasses and cassava are the two major feedstocks used in Thailand for bio-ethanol production although major production is from molasses. Sugarcane is a good feedstock for ethanol production since the crop is well adapted to the growing conditions of Thailand. According to OAE [8], it is ranked the second most economic crop of the country. Sugarcane is characterized by good yields even under low input of fossil energy [9]. This is an important aspect since for bioenergy to be climate friendly, it should be produced with minimum fossil input to ensure that ethanol is produced in a more sustainable way and the utilization of the by-products generated along the processing chain should be maximized. Sugar mills are therefore increasingly functioning as biorefineries, where molasses and sugarcane juice are used for ethanol production and other co-products for organic fertilizer production, and power and steam generation [10]. Some studies have shown that substantial GHG emission reductions can be achieved by replacing gasoline with ethanol from sugarcane and molasses [9,11]. This study aims at evaluating the environmental and socio-economic implications of molasses based ethanol production at a biorefinery complex where biomass utilization is maximized.

2. Status of Ethanol Production and Use in Thailand

Sugar plantations in Thailand occupy an area of about one million hectares mainly concentrated over 47 provinces in central, north eastern and northern Thailand. Although production of sugar fluctuates with weather conditions, the average yield for 2009 was about 66 tons/ha, that is a 10% increase as compared to 2007, but still lower than that of Brazil at 87 tons/ha [9,12]. Sugar production

over the last ten years has been ranging between 5–7 million tons [12,13]. About 30% of the production is used for domestic consumption, the rest being exported.

In 2009, ethanol production amounted to 400.7 million liters or 1.1 million liters/day. There are currently 19 ethanol plants in operation with a production capacity of 2.9 million tons per day. About 50% of the plants are flexible feedstock based ethanol plants; 60–70% of ethanol production is molasses-based since 70% of the ethanol plants have sugar mills as their core business. To satisfy the government target of three million liters per day by 2011, the number of ethanol plants in Thailand will increase to 23 plants in 2011 with a total production capacity of 4.6 million liters per day.

The use of gasohol in Thailand is not compulsory and premium gasoline (octane 95 gasoline) and regular gasoline (octane 91 gasoline) are still available at a price 10–15% and 22–26% lower respectively than E10 (10% ethanol blend with octane 91 gasoline). Hence, it is anticipated some consumers may not find the prices attractive enough to shift to E10, particularly those running on premium gasoline. Still, the biofuel promotion policy is meeting a certain amount of success in Thailand, shown by the increasing trend of gasohol consumption over the last five years, and up almost 50% in 2009 as compared to the previous year. Also the government is providing a series of incentives to stimulate ethanol production and consumption, including, excise tax exemption for ethanol producers selling ethanol in Thailand (of 8 THB/L), subsidies using the State Oil Fund to reduce the selling price of gasohol at the pump which enables refineries to lower the retail price of gasohol, and more advantageous excise tax reduction for car manufactures of vehicles running on E85 [7].

3. Biorefineries and Ethanol Production

As reported by Ribeiro Fernandes dos Santos [14], biorefineries are facilities that integrate processes for the conversion of biomass and equipment for the production of fuels, chemicals and energy from biomass resources. This is a similar concept to that of oil refineries which produce various products from crude oil. However, instead of using fossil based energy, as is the case for petroleum refineries, biorefineries rely on renewable, biomass-based raw materials.

The establishment of biorefineries has gained much interest worldwide with the promotion of renewable energy as a means to increase energy security for nations and to contribute to climate change mitigation, particularly with regards to global warming, based on the carbon neutral concept of CO_2 emissions from combustion of biomass materials [10].

As mentioned earlier, sugar mills in Thailand are integrated as the core business for ethanol production [7]. Also, there is a potential for utilization of by-products generated along the ethanol production chain. Hence, the development of biorefinery systems incorporating sugar mills and ethanol plants as their main processing units is of particular relevance in Thailand.

As part of the biorefinery system, there are several stages leading to ethanol production, *i.e.*, sugarcane farming, milling and ethanol production. At the farm stage, land preparation, planting, maintenance and harvesting are the main processes involved. Most steps are labor intensive except for planting which is fully mechanized [10]. Crop maintenance after planting (about one year) is a key factor influencing crop yield. It includes weeding as well as pesticide and fertilizer applications. The crops can be harvested 2–4 times before replanting is required as a result of reduced yield [15]. Generally burning is practiced before and after harvesting to ease the harvesting process and removal

of cane trash residues (tops and leaves) from the field. Such burning activities result in air pollution and losses of biomass materials that could otherwise be used for energy as well as soil management practices, particularly, to maintain soil quality (organic content and moisture) and avoid erosion [16]. Following harvesting, milling of the sugarcane takes place within 24 hours to avoid sugar losses. This operation produces sugar and two major by-products, bagasse and molasses. Bagasse is a biomass material that can be burnt in boilers at the mill for electricity and steam generation. Part of the electricity and steam can be used within the sugar mill while the excess electricity can be sold to the grid. This enables the mill not only to generate income from the biopower sold to the grid but also to gain GHG emission credits from the corresponding amount of fossil based grid electricity that has been displaced. In Thailand excess electricity generation per ton of cane as reported by [10], is in the range 14–15 kWh. This is quite a low range since 60–180 kWh are reported in the literature which can be further extended to several hundred kWh through optimization of cane field residues utilization and combustion in dedicated power plants [10,17,18].

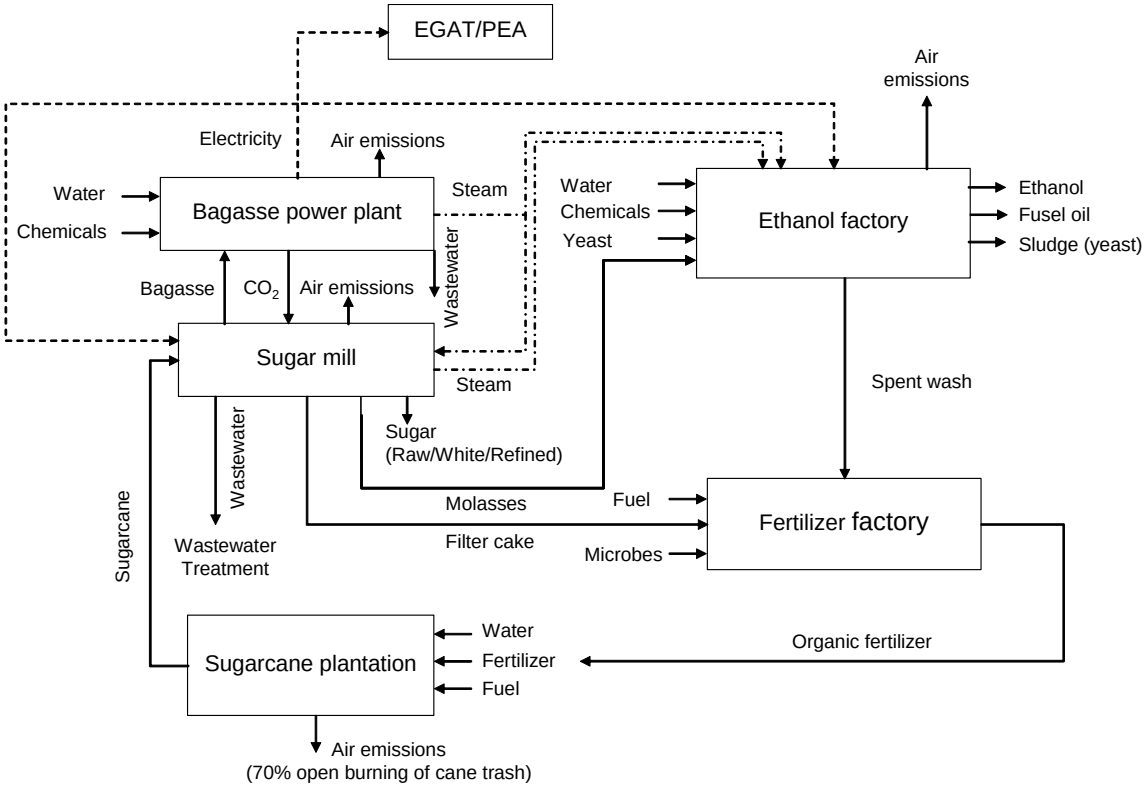
Ethanol production consists of the fermentation of molasses to produce a dilute alcohol solution which is followed by distillation and dehydration in order to produce fuel grade ethanol 99.5%. The three main by-products from this process are CO_2, stillage and wastewater. The CO_2 can be collected, purified and transformed for use in coolant, soft drink, soda, dry ice and fire extinguisher industries [19]. The solids contained in the slop supernatant can be separated from the stillage and utilized for energy via biogas generation, whereas the settled portion from the whole process can be used as manure/soil conditioner for sugarcane plantation [20]. Such utilization of by-products may contribute not only to optimize environmental performance via reduced GHG emissions but also to generate income.

4. Methodology

4.1. Biorefinery Complex in Thailand

The integration of several processing units described above into what may be referred to as a biorefinery complex where by-products utilization is maximized, may contribute to enhance the competitiveness of ethanol production as compared to separate production systems. To evaluate such aspects, a representative biorefinery complex in Khon Kaen province, Thailand producing molasses based ethanol was selected. The biorefinery complex includes sugarcane plantation and biorefinery as illustrated in Figure 1. Inputs and outputs from each unit of the biorefinery complex are highlighted, which include (1) sugarcane plantation (mainly contract farms), (2) sugar mill (bagasse based steam and electricity produced from boiler for internal use), (3) sugar power plant (steam and electricity from bagasse provided to sugar mill and ethanol plant and excess electricity sold to the grid), (4) ethanol plant and (5) fertilizer plant (sub-unit process of ethanol plant).

Figure 1. Molasses based ethanol production from a biorefinery complex.



4.2. Environmental Assessment Based on GHG Emissions

The environmental assessment was performed by assessing the GHG emissions associated to molasses-based ethanol production from the biorefinery complex and its ultimate use for transportation. The standard Life Cycle Assessment (LCA) methodology based on ISO 14040 was used to quantify the global warming potential over a 100 year-time horizon and expressed in units of CO_2 equivalent [21,22]. Other indicators such as abiotic resources depletion, acidification or eutrophication could have also been considered. However, due to major concerns worldwide surrounding the impacts of fossil energy use on climate change, notably from the use of fossil fuel in the transportation sector, global warming was selected as the main indicator for environmental assessment in this study. To perform such evaluation, input-output data, or so called "Life Cycle Inventory" (LCI) data, were collected for each production unit of the biorefinery complex including, sugarcane plantations, sugar mill, biomass power plant, fertilizer plant, and ethanol plant. Data gaps (transportation distances between various production units for instance) were addressed using academic assumptions based on data available from the study site or values retrieved from the literature. The reference flow (RF) chosen for the study is 1,000 kg of sugarcane corresponding to 14.95 L of ethanol (E100). In the environmental analysis, the emissions associated with facilities construction e.g. manufacturing machines, irrigating structures, buildings, infrastructures, vehicles, *etc.* as well as manual labor e.g. new planting, pruning, harvesting, machine operating, driving *etc*., were excluded.

Two scenarios were considered and results analyzed in comparison to that of the base case scenario illustrated in Figure 1.

Scenario 1 at the plantation, open burning of cane trash is being practiced prior to harvesting sugarcane. Two sub-scenarios were assessed in this study, 35% burning and 0% burning, and results compared to that of the base-case scenario where 70% of cane trash is being burnt.

Scenario 2 at the biorefinery, steam is being produced (sugar mill and power plant) and the excess fraction of steam is currently left un-used, *i.e.*, considered as a waste. In this scenario, the environmental implications related to the use of the total amount of steam produced from the biorefinery complex (total energy from steam) including left-over steam, was assessed and results compared to that of the base-case scenario.

4.3. Socio-Economic Assessment

4.3.1. Social INDICATOR

In order to assess the social impacts of the biorefinery complex on sugarcane farmers and employees of the biorefinery, the Human Development Index or HDI was considered. The purpose of this indicator is to evaluate how a biorefinery complex influences social welfare. The results obtained were compared to that of the population in the province where the biorefinery complex is located. To assess Human Development Index, three parameters are required according to the formula provided by UNDP [23] and reported below in Equation 1.

$$HDI = 1/3\ (LE + EI + GI) \quad (1)$$

where LE: Life Expectancy Index; EI: Education Index (based on Gross Enrolment Index and Literacy Rate); GI: Gross Domestic Product Index

Information for each of the parameters shown in Equation (1) was collected via questionnaire surveys where farmers at sugarcane plantations and workers at the biorefinery were interviewed. Also, information relating to salary scale of different category of workers was collected from annual reports of the biorefinery. For the population living in the province where the biorefinery complex is located, data were obtained from reports.

4.3.2. Economic assessment

For the economic assessment, total value added was selected as indicator. Assessments were made at the level of the sugarcane plantation and biorefinery. In order to estimate total value added, three main factors were taken into consideration including, total net profit, wages (employment) and tax revenues. Some details about each of those parameters are provided below.

Total Net Profit is the sum of the net profit generated from the main products (*i.e.*, sugarcane, sugar products, and ethanol) and by-products (*i.e.*, bagasse, molasses, fertilizer, electricity) after deduction of taxes and costs of operation. At the level of the sugarcane plantation, the annual net profit was calculated by deducting 0.75% withholding tax and farming costs to the annual income generated from selling sugarcane to the biorefinery. At the level of the biorefinery, net profit was calculated by deducting total income (total revenues from operations) with 35% corporate income tax, and total costs and expenses. Data for calculation were collected via interviews and questionnaire surveys as well as from company annual reports.

Wages for farmers at the sugarcane plantation and employees at the biorefinery were investigated and expressed in terms of man-days. Based on availability of data, some conversions were performed to express man-days into number of persons hired and estimate wages paid.

Tax revenue is the income generated by the government from the entities involved in each production process. At the plantation, taxes are collected from the sugarcane sold by farmers to the biorefinery. At the biorefinery, taxes are collected from each processing unit. However, in Thailand, ethanol factories and biomass power plants are exempt from paying taxes for a certain number of years, a situation which is applicable under the condition of this study. Hence, taxes were only collected from the production stage of sugarcane and the sugar mill. As reported earlier, a withholding tax of 0.75% is to be considered for the sugarcane plantation, while a corporate income tax of 35% is to be included for the biorefinery.

5. Results and Discussion

5.1. Global Warming Potential (GWP)

Based on the life cycle inventory data collected from the sugarcane plantation and biorefinery, the environmental impact resulting from the emissions of greenhouse gases (GHG) *i.e.*, CO_2, N_2O and CH_4, was estimated in terms of GWP per RF for each of the scenarios considered in this study. The results obtained are presented in Table 1.

Table 1. Life cycle results of Global Warming Potential (GWP) for each scenario of ethanol production and use and compared to gasoline.

	Ethanol (kg CO_2e)				**Gasoline**
	Base Scenario	Scenario 1		Scenario 2	**(kg CO_2e)**
		0%	35%		
Production	13.50	5.91	8.38	11.20	5.04
Use	-	-	-	-	21.66
Total	13.50	5.91	8.38	11.20	26.70

Remark: Results based on reference flow of 14.95 L ethanol which is equivalent to 9.89 L gasoline [24].

The sugarcane biorefinery results in an almost 50% reduction for ethanol as compared to gasoline. In fact, the reductions increase even further when cane trash burning is reduced (~70%) or avoided (~80%). A reasonable amount of GHG savings can also be obtained from utilization of steam that is currently left unused (an extra 10%).

The maximum contribution to the life cycle GHG emissions of ethanol is from the plantation stage at 13.65 kgCO_2e for the reference flow of 14.95 L ethanol, followed by transportation at 4.9 kgCO_2e. However, credits obtained from excess electricity sold to the grid help reduce the emissions by about 6.5 kgCO_2e. Open burning of cane trash and use of chemical fertilizers comprises the major GHG emission sources at the plantation stage, indicating the importance of proper management at this stage. Also, if the cane trash would be utilized for power production, this would further reduce GHG

emissions. However, this usage would require further investigation based on the properties of cane trash, logistics, *etc.*

The above results show that a biorefinery complex enables to maximize the utilization of the by-products generated along its processing units and to contribute reducing GHG emissions and therefore the GWP associated to molasses based ethanol production. It is also observed that there is still opportunity to further optimize the environmental performance, notably if the sugarcane residues produced at the plantation stage could find an alternative usage as a source of energy for instance, rather than being open burnt as currently practiced. This could provide additional GHG emission credits, benefiting the biorefinery complex and hence the environmental performance of molasses based ethanol as compared to gasoline.

5.2. Socio-Economic Implications

5.2.1. Human Development Index

HDI was determined separately for sugarcane farmers and employees at the biorefinery, and for the general population of Khon Kaen. As mentioned earlier, HDI is calculated through life expectancy index, education index and GDP index. With regards to education index, the value available at national level was used to perform the assessment since Thailand is characterized by a high literacy rate and gross enrollment which is assumed to be representative for every part of the country. In terms of life expectancy, the national figures were also used for the same reason as above. However, for GDP index, since there are large differences of income among social categories and regions in Thailand, specific information was collected for the biorefinery complex studied and the general population of Khon Kaen. Based on the data collected, GDP index was estimated accordingly for farmers at the sugarcane plantation, employees at the biorefinery, and population at the provincial level, as shown in Table 2.

Table 2. Calculation of GDP index for Khon Kaen province, plantation and biorefinery.

		GDP index
Gross Provincial Product per capita of Khon Kaen province	76,055 THB	0.673
Gross Provincial Product (PPP) per capita for Khon Kaen province	5,637 USD	
Income per capita for sugarcane plantation	47,100 THB	0.593
Income per capita (PPP) for sugarcane plantation	3,491 USD	
Income per capita for biorefinery	141,021 THB	0.776
Income per capita (PPP) for biorefinery	10,452 USD	

Remarks: 1USD = 33.38 THB [25];
Purchasing Power Parity (PPP) factor for Thailand is 2.47 [26].

For each category of population considered in this study, HDI was estimated based on the above assumptions, and the results are provided in Table 3.

Table 3. Calculation of Human Development Index (HDI) for Khon Kaen province, plantation and biorefinery.

Social Assessment	Khon Kaen	Sugarcane Plantation	Biorefinery
Life Expectancy at birth Indicator	0.728 *	0.728 *	0.728 *
Education Index	0.888 *	0.888 *	0.888 *
GDP Index	0.673 **	0.593	0.776
HDI	0.763	0.736	0.797

Remarks: * National data from UNDP [27]; ** GI calculated based on GPP of Khon Kaen [23].

From the results presented in Table 3, it is observed that the HDI of the farmers is lower than that of the general population in Khon Kaen. On the other hand, the HDI of the employees at the biorefinery is higher than that of the province. The parameter contributing to this result is the GDP index and is due to the difference in income as shown in Table 2.

Although the biorefinery complex set in Khon Kaen has not enabled the farmers to reach a level of social development that is higher than that of the provincial level, this negative change in HDI may not reflect the benefits that might have resulted from their contract with the sugar mill. Via contract farming, farmers are provided with a steady income for the year since their product (sugarcane) is guaranteed to be bought by the mill. This safety of a minimal income for the year is not captured by HDI, but is an important social aspect for farmers. Indeed, farmers in Thailand belong to a lower income class of the society and are therefore characterized by a social development that is lower than that of the average for the country. A comparison of their HDI with that of an average farmer in Khon Kaen (or national level) might show a positive change in HDI. This could be an additional option to assess if sugarcane farmers are really benefiting from their activities via contract farming with the sugar mill. On the other hand, employees at the biorefinery benefit from higher income and therefore living conditions which translate into a HDI that is higher than that of the province. Since HDI is an indicator that has been developed to assess level of social development at national level, those results show that there are still limitations in its use as a social indicator at sub-national levels and the results obtained should be interpreted with care.

5.2.2. Total value added

With regards to economic assessment, total value added from the sugarcane plantation and biorefinery was considered. The information was calculated based on several factors including net profit, wages and taxes. The overall results are presented in Table 4.

Table 4. Total value added per year from sugarcane cultivation and biorefinery.

Economic Assessment	**Life Cycle Stage**		Biorefinery complex (THB/Year)
	Plantation (THB/Year)	Biorefinery (THB/Year)	
Total Net Profit	393,681,432	956,712,601	1,350,394,033
Wages Paid	708,125,095	760,810,000	1,468,935,095
Tax Revenue	13,625,940	357,494,553	371,120,493
Total Value Added			**3,190,449,621**

Overall results from the biorefinery complex, as shown in Table 4, indicate that total net profit and wages combined represent 88% of the total value added, the remaining 12% being contributed by taxes. Hence, salaries and profits are major benefits. Taxes are contributing the lowest share since the Thailand Board of Investment has promulgated a regulation on biomass utilization where ethanol factories and biomass power plants are exempt from paying taxes for a certain number of years.

At the level of the sugarcane plantation, major contributors to total value added are the salaries paid to farm laborers for their cultivation activities, almost 64% of total value added, and from profits generated out of the selling of sugarcane to the mill, about 35% of total value added. Tax revenue contributes the remaining 1%. Therefore at the sugarcane plantation level, income generated out of the farming activities and selling of sugarcane to the mill are major economic assets; the farmers themselves are mainly benefiting from the activities associated to the biorefinery complex. Those are important indicators since they imply that living conditions of farmers are likely enhanced. Although the results of the economic assessment show economic benefits for the farmers which could lead to improved social development, results from the social assessment (HDI) did not confirm such an improvement since the information is not directly captured by HDI. It is therefore necessary that the results from the economic and social assessments be evaluated in combination in order to come up with a better understanding of the impacts of the biorefinery complex on the people.

At the level of the biorefinery, the results show that profit is a major contributor to total value added, about 46%, followed by salaries of employees at about 37%. Taxes are contributing 17% of the total value added. The economic assessment at the level of the biorefinery provides results that are quite different from those obtained at the level of the plantation. Profits are major assets to secure sustainability of operations of the biorefinery complex and represent therefore the largest share of total value added.

6. Conclusions

The environmental and socio-economic impacts related to a biorefinery complex producing molasses-based ethanol were assessed in the Khon Kaen province of Thailand using three major indicators.

For the environmental assessment, global warming potential was considered as the indicator. GHG emissions from the production and use of molasses-based ethanol for all scenarios considered were 50–80% lower than gasoline. The optimized use of biomass was found to contribute an important role in enhancing the environmental competitiveness of molasses based ethanol. It must be noted here that although global warming potential was considered in this study as the sole indicator for assessing environmental sustainability, other relevant indicators such as abiotic resource depletion could be included to further capture sustainability. Biofuel utilization should assist in slowing down the depletion of non-renewable energy resources and, as mentioned earlier, to contribute national energy security from avoided importation of fossil based energy which would contribute to bringing economic savings for the country.

With regards to social assessment, HDI was considered as the indicator. It was found that the HDI of farmers is lower than that of employees at the biorefinery. Still, their living conditions are expected to have improved from the steady income received as a result of contract farming with the sugar mill.

For the employees of the biorefinery, it was observed that their HDI is higher than that of the general population in the province, reflecting a higher level of social development. Although these results confirm that the biorefinery complex has enabled to bring social benefits particularly for employees at the biorefinery, certain limitations in the use of HDI were identified. These are due to the nature of the indicator which has been designed for assessment at national level. Also, it is obvious from the assessment performed in this study that the GDP index strongly influences the final results obtained for HDI. This shows that it is important to not dissociate social and economic assessments since both are interlinked and therefore influence each other. Thus, a socio-economic assessment in which results from both aspects are interpreted in combination is most appropriate to capture sustainability and avoid misleading or biased interpretation of the results obtained. This case is particularly well illustrated for the farmers who did not seem to benefit socially from their activities with the biorefinery. However, the economic assessment revealed that farmers are those mainly benefiting from the biorefinery activities at the plantation stage since wages and profits from selling sugarcane to the mill were found to represent the largest fraction of the total value added. Contract farming is the scheme which has brought such benefits to farmers, not only by the positive economic impact but also socially, even though this was not really captured by HDI.

Acknowledgements

The authors gratefully acknowledge the support provided by the Economic Research Institute of ASEAN and East Asia (ERIA). The comments and suggestions of the expert working group on "Sustainable Biomass Utilisation Vision in East Asia" are also acknowledged

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