Sugarcane Biorefinery Complex in Thailand and a Proposed Method to Cope with Apportioning Its Environmental Burdens to Co-products

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Abstract: This paper considers the effect of different allocation methods on life cycle assessment (LCA) results of products derived from a sugarcane biorefinery complex in Thailand. Issues from various allocation methods to a system of sugarcane-based production in the case of closed-loop recycling were discussed as an example for further applying with such a bioenergy system. The greenhouse gas (GHG) associated with the production of sugar, electricity, steam, ethanol, and organic fertilizer originated from sugarcane was investigated, considering all methods guided by ISO (2006) for partitioning emissions from the process i.e. avoiding allocation, mass allocation <MA> and economic allocation <EA> as well as approaches of recent allocation like energy allocation <EnA>, exergy allocation <ExA>, and hybrid allocation. The study also considered a case assuming that wasted steam remaining from the overall process is totally utilized, to observe the decrease of emissions shared to each product after this positive change as a potential process improvement, since it is the largest energy lost according to the company's recommendation. The results show large variations in GHG amount for each case and order of contributor can be sensitively changed depending on which allocation method is selected. <EnA> was found to be most suited to the system while irrational characteristics were unveiled for the others.

Keywords: Sugarcane biorefinery, industrial ecology, life cycle assessment (LCA), greenhouse gas (GHG), allocation method.

1. Introduction

In accordance with Thailand's energy policy to promote energy conservation, increasing of biofuels utilization has been targeted not only for attaining energy security, helping alleviate the current economic crisis and supporting labor employment in the rural areas but also for addressing the global warming problem [1-3]. The purpose of sugarcane cultivation, the second most economically important food crop of Thailand [4-5], has mainly been to produce food for human consumption until the recent past. More recently, it has become an important source of biomass energy production since 70-80% of the 4.2 million liters ethanol production per day from the whole country in 2014, were molasses-based. Furthermore, there are other obtainable byproducts e.g. electricity, fertilizer, etc. [6-9].

Anyway, to produce such byproducts, an additional amount of energy and natural resources are required. To ensure that the effort to acquire those sugarcane-based products really provide benefit, life cycle assessment (LCA) is an appropriate methodology for evaluation and has been used as a tool by many researchers [10-11]. Applications of different LCA methodologies are accepted to take care of the unique complexity of each situation leading to a wide range of results even in the same product life cycle. One of the open methodological issues is the allocation of emissions to the co-products providing a huge influence on final results [12-13]. Although the International Organization for Standardization (ISO) developed a stepwise standard approach for dealing with co-product allocation in the ISO 14044 standard for LCA [14], multifarious allocation methodologies still have been applied for many published works, for example; energy allocation in a case of seafood production system [15] and a case of petroleum refineries to petroleum products [16], protein allocation in a case of milk production [13], and exergy allocation in a case of power and steam production [17]. Various allocation methods e.g. economic, energy, hybrid allocation, etc. have been employed for several cases of assessing sugarcane-based product system [7, 18-20]. This study aims to evaluate the consequence of that disparity and if it is significant, a suitable allocation method for such a sugarcane biorefinery.

2. An Overview of Sugarcane Biorefinery Complex in Thailand as Currently Promoted for Industrial Ecology

Similar in concept to oil refinery producing various products from crude oil, operation of biorefinery is the integration of facilities to alter biomass resources to fuels, chemicals, etc. as reported by Ribeiro Fernandes dos Santos [21]. For the biorefinery system of sugarcane-based ethanol, there are several main stages leading to ethanol production, i.e., sugarcane farming, sugar milling and bioethanol production with high potential of producing various byproducts.

The area occupied by sugarcane plantation in Thailand is around 1.6 million ha [22]. Average yield of sugarcane production in Thailand is about 66 tons/ha (while that of Brazil is at 87 tons/ha) [23-24], resulting in the sugar yield ranging 5-7 million tons [24-25]. Cane leaf residue both from stalk cutting and from milling process has been somewhere used as soil conditioner [26-27, on-site data].

In the milling process, apart from sugar which is the major product of this production system, bagasse, filter cake, and molasses are also valuable. Bagasse is a biomass remaining from crushing cane stalk that can be burnt for electricity and steam generation. Filter cake is considered as soil conditioner for plantation [28]. Molasses can be both an ingredient in livestock feed and raw material for ethanol production [19]. Production of molasses-based 99.5% ethanol comprises fermentation, distillation, and dehydration processes. CO_2 and stillage obtainable from ethanol production can be alternatively used as raw material for the next manufacturing process. CO_2 can be theoretically collectable from fermentation process and utilized in coolant, soft drink, dry ice, fire extinguisher, etc. [29]. Proper mixing of stillage and filter cake from sugar mill can reach the organic fertilizer standard for sale in Thailand [7, 30-31, on-site data]. Moreover, in wastewater ponds, biogas can be technically generated from the stillage [19].

With the performance to substitute material and energy supplies by renewable sources, this system represents the characteristics of industrial ecology since it shifts its precedent status from linear system, where some outputs obtained become wastes in vain, to closed loop systems where those materials become inputs for internal processes [32].

3. Methodology – Environmental Assessment Based on GHG Emissions

Due to the concern worldwide on climate change, GHG emissions associated to activities of biorefinery complex were assessed as a representative indicator for the study's objective. Based on the standard Life Cycle Assessment (LCA) methodology – ISO 14040; the global warming potential was investigated over a 100 year-time horizon expressed in unit of CO_{2eq}, counting CO_2, CH_4 and N_2O emitted from the system so as to figure out overall environmental load and share to individual products with apposite allocation method [33-34]. Further from the actual case, this study also contributes LCA results assuming that all product outputs of the sugarcane biorefinery complex are ultimately utilized.

3.1 Study scope & system description

Study boundary of this complex system covers 6 main stages i.e. 1) sugarcane cultivation, 2) sugar refining, 3) molasses-based ethanol production, 4) bagasse-based power production, 5) fertilizer production, and 6) all intermediate transportation. Calculation flow for this LCA study is the production of sugar, electricity, steam, ethanol, and fertilizer ready at factory gate derived from 1 tonne of sugarcane. The data of this study is based on a real site in the northeast region of Thailand. The site's milling period is normally during December – March. The range of sugarcane yield from over 3,500 of the site's farm contracts is around 55-120 ton/ha. The facilities' maximum capacities of this company group per year i.e. sugar mill, turbine generators, alcohol factory, and fertilizer factory are around 2.9 MT sugarcane, 400 GWh electricity, 5 MT steam, 45 ML ethanol, and 0.1 ton fertilizer (NPK: 2.5-3.0, 2.5-3.0, 3.0-4.0 % w/w). The generated energy is sufficient for running the whole business group and supplying electricity to the Provincial Electricity Authority (PEA). The transportation distance from farm to sugar factory are divided into 3 zones; near (25 km), medium (25-50 km), and remote (50-80 km). Statistical percentage of sugarcane yield from near, medium, and remote zone is 40%, 30%, and 30% respectively. The distance from sugar factory to power plant, ethanol factory, and fertilizer factory is 0.4 km, 0.8 km, and 12 km in the same direction.

Different from other sub-factories that have their own rights to set annual production targets, the power plant has a strict contract with PEA to supply at least 20 MW of electricity continuously for 20 years. However, agro-based manufacture has to rely on weather conditions and unpredictable rainfall. The sugar factory was able to collect just 1.9 MT of sugarcane in the season in which the data was collected, which was very low compared to facility's capacity (2.9 MT of sugarcane); however operation at less than 100% capacity was a frequent occurrence. Amount of bagasse varied according to the sugarcane yield but was still sufficient to produce electricity for supply to PEA and self-utilization. In rare cases, bagasse and other biomass materials are imported from nearby sugar factories. Such a practice due to deficient yield happens merely in drought years.

3.2 Allocation

After reviewing practicable methods to deal with multi-products in LCA study of bioenergy system available in publications [12, 17, 20, 35], the methods considered for the discussion in this study are as follows:

3.2.1 Avoiding allocation

According to ISO 14044 standard for LCA, "wherever possible, allocation of the environmental burdens associated with the studied system should be avoided, by dividing the multifunction process into sub-processes, or by expanding the data related to these sub-processes, or by expanding the product system to include the additional functions related to the co-products" [15].

Dividing a multifunction process into sub-processes is a flexible option causing a change in the study results [16]. For LCA study of sugarcane-based products, this difference also happens at the process of power generation either to group it into the same production unit with sugar production or separate it out [7, 20, 36]. However, the actual aim of dividing sub-processes is to avoid allocation but from the overall perspective, the result can turn into more steps of allocation. In other words, the issue between these considerations is whether the allocation of emissions to bagasse will take place. Allocation flow diagram of the two schemes for the comparison of that dissimilarity is shown in Fig. 1.

Another way of avoiding allocation, system expansion generally considered in consequential LCA study, has also been suggested by Nguyen and Hermansen as an adequate method for handling co-products in LCA of sugar cane bio-energy systems when the purpose of the LCA is to support decision makers in weighing the options and consequences. Nevertheless, system expansion is inapplicable for this case study, considering steam as co-product, opposite to Nguyen and Hermansen's case where steam remaining from overall process is neglected [19]. Task of system expansion is to identify close substitutes for the co-product considered and their product systems. Yet, steam, gaseous phase of water, has many factors to be considered together e.g. mass, temperature, pressure, etc. and particular data for suitable compensation based on property of product is not available. Moreover, system expansion has limitation for this case if the interest of study is products as electricity, ethanol, fertilizer etc. because sugar cannot be fittingly substituted by other processes; sugar production from cane is traditional in Thailand. Use of this substitution method is also criticized to probably cause new allocation problems again when the system is expanded [37].

3.2.2 Mass allocation <MA>, Energy allocation <EnA>, and Exergy allocation <ExA>

"wherever allocation cannot be avoided, the environmental burdens of the system should be allocated according to an underlying physical relationship that reflects the way in which the inputs and outputs are changed by quantitative changes in the products or functions delivered by the system" [15].

Mass allocation <MA> will undoubtedly lead to irrational results in this case because one of the product outputs is electricity and it has no physical weight. <MA> for LCA study of sugarcane products was adapted in Australia's case by the combination of <MA> and <EnA>, so called hybrid allocation, for the energy products from bagasse combustion [20]. Hybrid allocation has a good advantage for its flexibility. On the other hand, with the purpose to find adequate practice of partitioning emissions to co-products, hybrid allocation should be avoided since it provides infinite available options. For example, just for one product as electricity, <MA> can be variously adapted with <EA>, <EnA>, <ExA>, and even with system expansion, conducted as attributional LCA. Even though hybrid allocation is not included in details in this study; preliminary investigation to ascertain its practicability is presented in Section 4 – results and discussion.

Energy allocation <EnA> reflects the relationships between the inputs and outputs of the system by gross energy content. <EnA> has been frequently used in LCA studies [17, 20, 38].

Exergy allocation <ExA> can be referred to the allocation of several names such as available energy, utilizable energy, availability, work capability, essergy, etc. with the same physical concept [32]. It is defined by Szargut as the maximum amount of work obtainable if a substance or a form of energy is transferred to a state of thermodynamic equilibrium (inert reference state). Exergy can, vice versa, be the minimum amount of work to be supplied if a substance or a form of energy has to be produced from its inert reference state [39]. Exergy is simply denoted as the value of product measured on the basis of work i.e. ability to produce work or work consumed to produce that form of exergy.

3.2.3 Economic allocation <EA>

"where such a physical relationship cannot be established, the allocation should reflect other relationships between the inputs and outputs of the system, such as economic value" [15]. Applied values for <EA> were the real prices directly collected from the study sites. Even though these factories are in the same company group, sale prices between factories basically are in the same range as market prices.

All mentioned cases will be compared together with an assumed scenario. As shown in Fig. 1, steam remaining from the process will be counted as one of the final products to see the result after this process improvement is developed. In fact, after steam is utilized for all possible purposes, an amount of steam is always wasted. This is due to the trend to demand the high amount of sugar and electricity while there is no plan to utilize all steam produced. Nonetheless, the factory realizes this and has a near future plan to make use of steam by trading with nearby factories via pipeline.

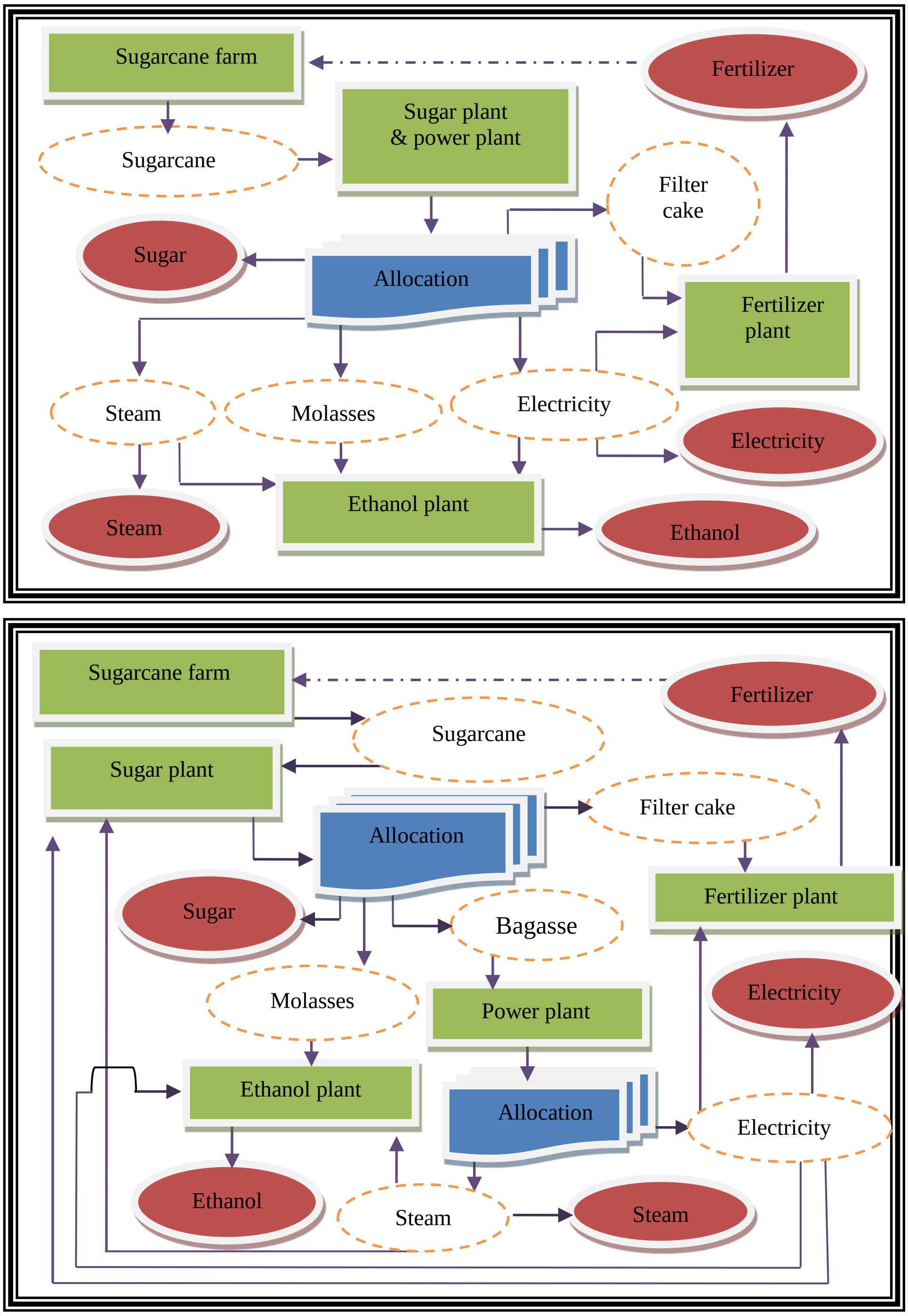

Figure 1. Allocation diagrams for the closed loop system of a sugarcane biorefinery complex:
< Scheme-a> (Above) turbine to generate electricity and steam is considered as facility of sugar factory
< Scheme-b> (Below) processes of sugar factory & power plant are considered separately

4. Results and discussion

Life Cycle Inventory (LCI): Input and output flow for the sugarcane-based production system and nearby sugar factories supplying bagasse and molasses to the system are summarized in Table 1. Per ton of sugarcane, the sugar factory can produce 99.6 kg of sugar and obtains 340 kg of bagasse which will be transferred by pipeline to the turbine generators of the power plant for producing 117.0 kWh of electricity and 617.3 kg of steam. About 9.6 kWh of electricity is required for internal use of power plant. Then, 31.8 kWh of electricity and 582.3 kg of steam generated from power plant are transferred back to sugar factory. The process of sugar production uses 96.6% by weight of total chemicals used in all factories; 75.4% is contributed by the NaCl for refinery and wastewater treatment process. Other main chemicals used are lime, phosphoric acid, and NaOH contributing 22.4%, 0.7%, and 0.4% respectively.

Molasses and filter cake are feedstock for the alcohol factory and fertilizer factory respectively. Stillage, sludge in wastewater from ethanol factory, is partially sent to mix with filter cake and microorganisms under controlled conditions to make organic fertilizer. Stillage left is returned to farm as one of the repayments for farmers who can supply the targeted amount of sugarcane as promised to the sugar factory. With the longest distance for transportation by pipeline, carrying stillage from ethanol factory to fertilizer factory possesses 88% of total electricity consumed for transportation. Carrying sugarcane by truck to factory and back trip with free load contributes 99.8% of total diesel consumed for transportation. For this study site, all transportation by truck has empty return.

Around 70% of cane trash from cane plantation is burnt during cane gathering period even though farmers know well that this can harm the soil quality. Yet, as the cost of harvesting fresh yield (with no burning) is over 1.5 times higher, even the promotion by sugar factory of extra-payment for yield with rich sugar content does not prevent this practice. Over 110 kg of cane trash from milling process is sent to factory's farming area together with ash from turbine generator as soil conditioner. Utilization of biogas from wastewater and CO_2 from fermentation process of ethanol factory is just in the plan. From processes explained, the factors for considering CO_{2eq} emissions released as well as the factors for each allocation method for all considered scenarios are shown in Table 2 and Table 3 respectively.

Further calculation factors for environmental assessment based on GHG emissions from Table 2 for over 30 kinds of chemicals used in all sub-factories are extracted from Ecoinvent database from SimaPro program version 7.1. Mass of chemicals used compared to others such as mass of sugarcane is very small. Therefore, CO_2 emissions caused by overall usage of chemicals are just 2.3% of the total emissions released within this factory. For the calculation factors shown in Table 3, economic-based allocation factors are obtained from factory while the others are obtained from literature and calculations. Energy-based allocation factor of molasses is calculated in the same way with that of sugar and bagasse (i.e. heating value) based on molasses' sugar content. Exergy-based allocation factors of sugar and molasses is extracted from literature, originally considering the exergy of sucrose-water solutions while that of bagasse is extracted from the same source using the calculation method for wood proposed by Szargut et al [51]. Energy and exergy-based allocation factors of filter cake are calculated based on the formula in literature for the calculation of specific chemical enthalpy and specific chemical exergy of matter respectively [47]. All the energy contained in electrical power is useful and is therefore equal for both energy and exergy-based allocation [48-49]. Based on steam energy used for thermal transference [50], exergy of steam can be calculated according to Formula 1 to specify the obtainable work from a heat source. The temperature for reference state is assumed at 25°C.

Table 1. LCI for the sugarcane-based production system [27].

1. Cane plantation	
Input	
Fertilizer – N	8.6 kg
Fertilizer – P2O5	9.0 kg
Fertilizer – K2O	4.3 kg
Diesel for farm operation	2.6 kg
Pesticides	0.1 kg
Output	
Cane stalk	1,000.0 kg
Cane trash (~70% burnt at farm)	159.0 kg
2. Sugar mill	
Input	
Cane stalk (from cane farm)	1,000.0 kg
Chemicals	14.3 kg
Electricity (from power plant)	31.8 kWh
Steam (from power plant)	582.3 kg
Output	
Sugar	99.6 kg
Molasses	42.1 kg
Filter cake	45.3 kg
Bagasse	340.0 kg
Cane trash & waste	113.8 kg
Wastewater (BOD 1.0E-4 kg)	0.9 L
3. Power plant	
Input	
Bagasse (from sugar mill)	340.0 kg
Chemicals	0.1 kg
Output	
Electricity	107.4 kWh
Steam	617.3 kg
Wastewater (BOD 5.2E-5 kg)	4.3 L
4. Ethanol factory	
Input	
Molasses (from sugar mill)	42.1 kg
Chemicals	0.3 kg
Electricity (from power plant)	0.9 kWh
Steam (from power plant)	28.2 kg
Output	
Ethanol	11.3 L
Wastewater (BOD 7.8E-10 kg)	1.5E-2 L
5. Fertilizer factory	
Input	
Filter cake (from sugar mill)	45.3 kg
Electricity (from power plant)	0.2 kWh
Diesel (operation of machine)	0.4 L
Chemicals	0.1 kg
Output	
Organic fertilizer	18.1 kg
6. Transportation	
Diesel: truck sugarcane (farm-sugar mill), filter cake (mill-fertilizer fac.), etc.	14.3 L
Electricity: pipeline sugarcane (farm-sugar mill), molasses (sugar mill-Ethanol fac.) stillage (Ethanol fac.-fertilizer fac.)	1.0 kWh
7. Final energy remaining from overall process	
Electricity (sale to PEA)	73.5 kWh
---Waste steam	6.8 kg

$$Ext\boldsymbol{h} = Q\boldsymbol{h} \times \frac{Th - Tc}{Th}$$ ------ Formula 1

$Ext\boldsymbol{h}$: Thermal exergy (MJ);

$Q\boldsymbol{h}$: Energy from heat source (MJ),

$T\boldsymbol{h}$: Temperature of the heat source;

Tc : Temperature of the environment

Allocation factors for scheme-a and scheme-b are summarized in Tables 4 and 5, respectively. The calculations in both tables are based on the amount of major products for allocation and factors presented in Table 3.

Life Cycle Impact Assessment (LCIA): Preliminary investigation of hybrid allocation shows rather inconsistent results from the combination of <MA> with <EA>, <EnA>, and <ExA>. Based upon scheme-b where the sugar factory and power plant are considered independently, separating the allocation of emissions to electricity and steam from the other products in the 2nd step [16], GHG emissions shared to fertilizer, in the case of hybrid allocation are 3-62 times higher than that for each individual case.

Table 2. Calculation factors for environmental assessment based on GHG emissions.

Item	**Factor**	**Unit**	**Remark**	**Ref.**
Fertilizer and herbicide		kg CO_{2eq}/kg	Production	[40]
- N (weighted average of 3 types of N-fertilizers)	3.00			
- P_2O_5	1.03			
- K_2O	0.69			
- Herbicide	25.3			
N_2O from fertilizer-N application	4.68	kg CO_{2eq}/N	0.01 kg N_2O-N/kg N	[34]
N_2O from soils amended with crop residues	4.68	kg CO_{2eq}/N	0.01 kg N_2O-N/kg N	[34]
Diesel	3.3	kg CO_{2eq}/L	Production and combustion	[40, 41]
CH_4 from anaerobic pond	5.52	kg CO_{2eq}/kg BOD stillage	CH_4 and N_2O emissions only, CO_2 not included	[42]
Cane trash (uncontrolled) open burning, 90% efficiency	0.097	kg CO_{2eq}/kg dry trash		[42]
Bagasse combustion in boilers	0.025	kg CO_{2eq}/kg		[40, 43]
Thai electricity (mainly natural gas based)	0.80	kg CO_{2eq}/kWh	Production	[40, 44]

Table 3. Calculation factors for each allocation method.

Product	**Economic-based (Baht/unit)**	**Energy-based (MJ/unit)**	**Exergy-based (MJ/unit)**
Sugar (kg)	13.00	16.18 [45]	17.55 [46]
Molasses (kg)	3.50	10.03 [45]	12.82 [46]
Bagasse (kg)	0.50	7.35 [27]	9.96 [46]
Filter cake (kg)	0.05	3.04 [47]	3.09 [47]
Electricity (kWh)	2.80	3.60	3.60 [48, 49]
Steam (kg)	0.35	2.72 [50]	0.69 [32]

Table 4. Allocation factors for Scheme-a.

Product	Amount	Economic allocation		Energy allocation		Exergy allocation	
		Price (THB/unit)	Allocation factor	Energy (MJ/unit)	Allocation factor	Exergy (MJ/unit)	Allocation factor
Sugar	99.6 kg	13.00	0.776	16.18	0.635	17.55	0.642
Molasses	42.1 kg	3.50	0.088	10.03	0.166	12.82	0.198
Filter cake	45.3 kg	0.05	0.001	3.04	0.054	3.09	0.051
Electricity	75.6 kWh	2.80	0.127	3.60	0.107	3.60	0.100
Steam	35.0 kg	0.35	0.007	2.72	0.037	0.69	0.009
Total			1.000		1.000		1.000

a = product value, b = calculation unit of each allocation method

Table 5. Allocation factors for Scheme-b.

	Product	Amount	Economic allocation		Energy allocation		Exergy allocation	
			Price (THB/unit)	Allocation factor	Energy (MJ/unit)	Allocation factor	Exergy (MJ/unit)	Allocation factor
1st step	Sugar	99.6 kg	13.00	0.802	16.18	0.345	17.55	0.301
	Molasses	42.1 kg	3.50	0.091	10.03	0.090	12.82	0.093
	Filter cake	45.3 kg	0.05	0.001	3.04	0.029	3.09	0.024
	Bagasse	340.0 kg	0.50	0.105	7.35	0.535	9.96	0.582
	Total			1.000		1.000		1.000
2nd step	Electricity	75.6 kWh	2.80	0.945	3.60	0.741	3.60	0.918
	Steam	35.0 kg	0.35	0.055	2.72	0.259	0.69	0.082
	Total			1.000		1.000		1.000

a = product value, b = calculation unit of each allocation method

The most significant difference is in the case of mass-economic hybrid allocation since the economic value of fertilizer is quite small but its total weight is high. Fertilizer, product mixed by mud with microorganism and sludge from wastewater possessing, is just encouraged as product for sale lately so as to utilize remnant from sugar milling process worthily.

For the main study, as shown in Fig. 2, all considered cases for real situation are abbreviated as case "a1-3" and "b1-3". Roughly, regardless of GHG value shared to each intermediate product in unit kg CO_{2eq} for each allocation method, the proportion of CO_{2eq} between each case is very similar especially for the cases a2, a3, and b2. For every case, sugar production, the major process for this business group, is the largest contributor. However, the major divergence is in the 2nd and 3rd order of burden contributors. Electricity production is the 2nd largest contributor for case a1 and b3 while ethanol production is the 2nd largest contributor for the remaining cases (a2, a3, b1, and b2).

The reasons for this dissimilarity between these 6 cases are as follows: For case a1, allocation factors of molasses and electricity are not much different. The result is simply shown based on quantity of product. For cases a2 and a3, allocation factors of molasses are higher than that of electricity by 1.6 and 2.0 times respectively. Allocation loaded to ethanol is consequently higher than that to electricity. For Scheme-b, mainly due to the step of allocation having bagasse as intermediate product, these 3 cases have dissimilar percentages of GHG contribution. The burden load from the total emissions for the 1st step-allocation shared to bagasse is 11%, 54% and 58% for b1, b2 and b3 respectively. The result of b1 case is different from that of b2 and b3 cases because the gaps of value between bagasse and other products i.e. sugar and molasses are huge – 7-26 times in the case of <EA> but they are just 1.4-2.2 and 1.3-1.8 times in the case of <EnA> and <ExA>, respectively. This is why the emission load shared to electricity for b1 is lower than all other cases. The difference between b2 and b3 is mainly due to the share of emission to electricity and steam at the 2nd step-allocation. The ratios of contributed emission load between electricity and steam for b2 and b3 are 0.74:0.26 and 0.92:0.08 resulting in the higher emission load contributed to steam for b2 case, which will be shifted to milling and ethanol production processes afterward. So, emission burden loaded to ethanol will become higher than that to electricity for b2.

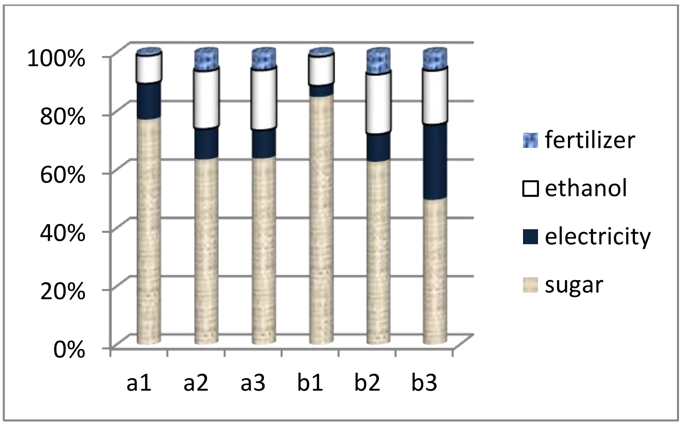

Figure 2. CO_2eq shared to each final product based on considered allocation methods:
a1, a2, and a3 represent emissions shared to products based on <EA>, <EnA>, and <ExA> respectively for Scheme-a;
b1, b2, and b3 represent emissions shared to products based on <EA>, <EnA>, and <ExA> respectively for Scheme-b

Regarding the justification for the selection of allocation method, the significant issues should be considered together. To explore the variation between <EA>, <EnA>, and <ExA>, the CO_2eq balance for simpler flow as Scheme-a is outlined in Fig. 3 in the assumed case that remaining steam is fully utilized so as to further observe how much emissions shared to each product can be minimized from the improvement. Prior discussion will be given to <EA> presenting slightly different results from <EnA> and <ExA>. The strong point of <EA> is its characteristic to fairly represent the value of product with the concept of monetary basis. Unfortunately, it is not suited for this case with the same company group because some product price between factories is not decided based on real market price but it is sometimes to support any production unit in the specific situation. Several factory groups like this case also split the system into multi-sub companies and each company has the right to find raw material by its own management relying on market price so as to increase the competition capability. Another actual aim for separation of single large company to multi-sub companies is to decrease the cost of taxation from

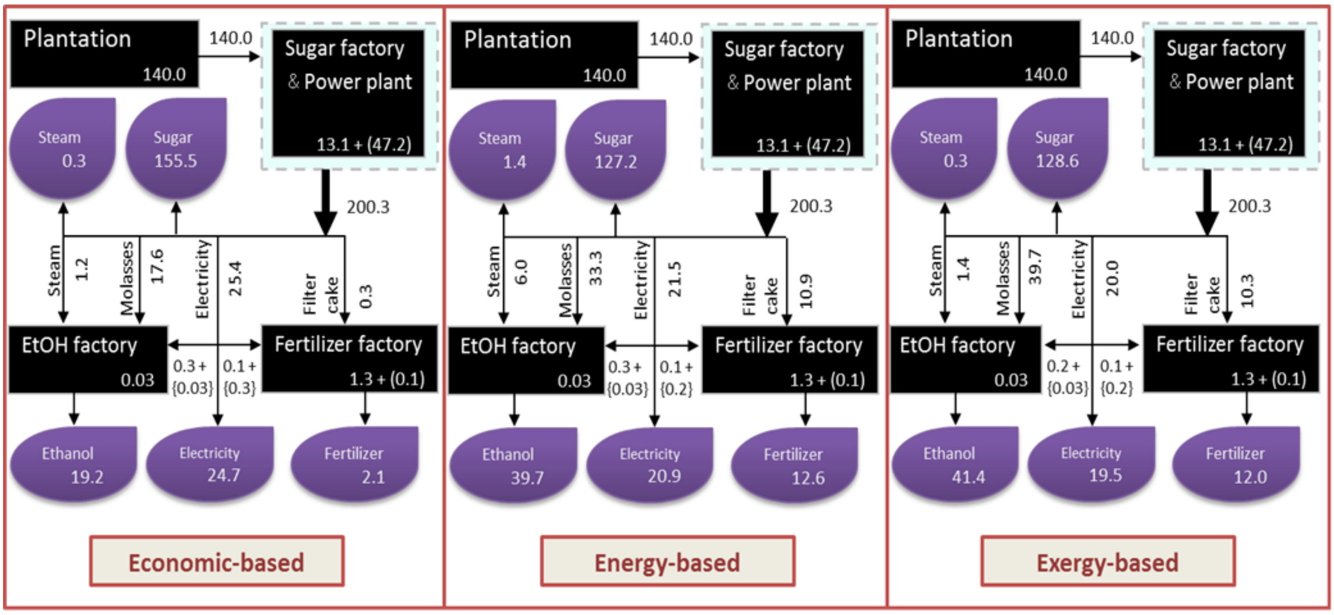

Figure 3. CO_2eq balance of a sugarcane biorefinery complex, Scheme-a (…) and {…} represent diesel and electricity consumption respectively for the transportation between former and the identified processes.

progressive income tax. An example in this case is at the price of filter cake which is raw material for producing fertilizer. Cost of filter cake and stillage is 0.05 Baht/kg and free of charge respectively while the sale price of organic fertilizer is 5 Baht/kg which is 100 times different from cost of major material for the production. CO_2 emissions allocated to filter cake for <EA>, <EnA>, and <ExA> are therefore 0.3, 10.9, and 10.3 $kgCO_{2eq}$ respectively. For filter cake, there is no large significance in term of value for the selection of <EnA> and <ExA> while for <EA> , the allocation factor does not reflect the real value due to the financial support by the sugar factory – the main company.

Moreover, <EA> factor is not always acquired simply. Real product price between suppliers is regularly confidential. Furthermore, as it is sometimes called the market-value-based method, its most noticeable weak point is the fluctuation of market price relying on the period of time affecting the result. In addition, prices of products for each country are different resulting in the dissimilar standards to explore environmental burdens while the environmental issue is evenly raised to be discussed at international fora.

If <EA> is regarded as monetary basis, <EnA> and <ExA> can be obviously considered as scientific basis. From Fig. 2, in case of Scheme-a, there is no difference between <EnA> and <ExA> for the order of environmental burden contributor and the GHG value loaded to each product is very close while it is not so in Scheme-b. However, in detail for the assumed case of using all remaining steam from Fig. 3, even for Scheme-a, there is an imperative issue for the difference of allocation factors for <EnA> and <ExA> of steam that cannot be overlooked. From sugar factory (and power plant), environmental burden loaded to total electricity and steam right after the allocation for <EnA> is 21.5 and 7.4 $kgCO_{eq}$ while for <ExA> is 20.0 and 1.7 $kgCO_{2eq}$. That difference is visibly emerged in Scheme-a with just taking 6.8 kg of waste steam (per calculation flow or ~12,920 ton for this season) into account. The data considered in this study can be the representative for normal situation of sugar biorefinery processing chain. Nonetheless, in some years the factory obtains a massive amount of sugarcane to achieve the maximum production of sugar mill, resulting in the higher amount of remaining waste steam. That might rather affect the proportion of CO_{2eq} contribution between <EnA> and <ExA>.

A clearer example to explain the difference between <EnA> and <ExA> can be seen from the cycle heat balance of a turbine generator of the power plant as shown in Fig. 4. Process diagram starts at input of 200 ton/h of bagasse with 1,470 GJ/h of total heating value. After burning bagasse, this can produce high pressure steam with 423 GJ/h of total heating value. Around 274 GJ/h of thermal energy is required in the process for transferring to 101 GJ/h of electrical energy. Byproduct from the process is low pressure steam with 149 GJ/h of total heating value. Consideration of only heating value between electricity and low pressure steam signifies the higher amount of energy for the latter. Nevertheless, with the concept of available energy, total exergy value of low pressure steam is just 38 GJ/h, quite lower than 101 GJ/h for that of electricity.

For the selection of allocation method, <EnA> is rather recommended than other allocation methods for such a production in Thailand. The reason is the robustness of <EnA> result that the burden values for final products are the same for both Scheme-a and Scheme-b as presented in Fig. 2. Compared to Scheme-b, practice of Scheme-a is more convenient to avoid the complication of loop allocation. However, in some case, assessors may not be able to select the preferred option by themselves. Scheme-b is in the case that data for turbine generator and sugar factory can be really divided as an individual unit. Scheme-a is necessary when the data between sugar factory and power plant is undividable.

A noticeable point from the results of <EnA> case (a2 and b2) as well as a3 and b1 is the close values of environmental loads to electricity and fertilizer. As mentioned upon, fertilizer is just a newly promoted product in recent years with unstable status. Many factories in Thailand still ignore and manage stillage and filter cake like waste. Fertilizer production unit might not be able to rely on itself without support while the electricity is considered an imperative and stable status at least in the amount as annual contract signed with PEA. Nevertheless, the correspondence of 4 from 6 study cases can indicate that the factory have made the right and significant decision to invest money to construct a small factory so as to turn waste like stillage and filter cake into fertilizer, which is comparable with electricity in terms of GHG reduction. The utilization of stillage and filter cake should be promoted like it was done for electricity a decade or so ago. The valuable points in favor of this practice are to maintain soil quality, reduce the use of chemical fertilizer, and increase moisture of soil, etc. contributing to the sustainability of this business [52].

An environmental benefit can be also accomplished if the average environmental impact of all products on the market is diminished. A possible way to achieve this is when the customer can "visualize" the environmental burden of products shown on shelves in the market so that they can compare and choose to support the products with less impacts. Nevertheless, LCA results of sugarcane biorefinery system are very sensitive to allocation methods. Overall environmental impacts individually communicated to the society from each company can be much lower than the existing situation if the best environmental performance adjustable by speculative methodology as "allocation" is intentionally selected to present. Either attached information such as allocation method, etc. must be strictly requested whenever a product's environmental performance is communicated to the customers or a standard method causing conflict like allocation should be standardized case by case for each multi-product life cycle by accredited organizations.

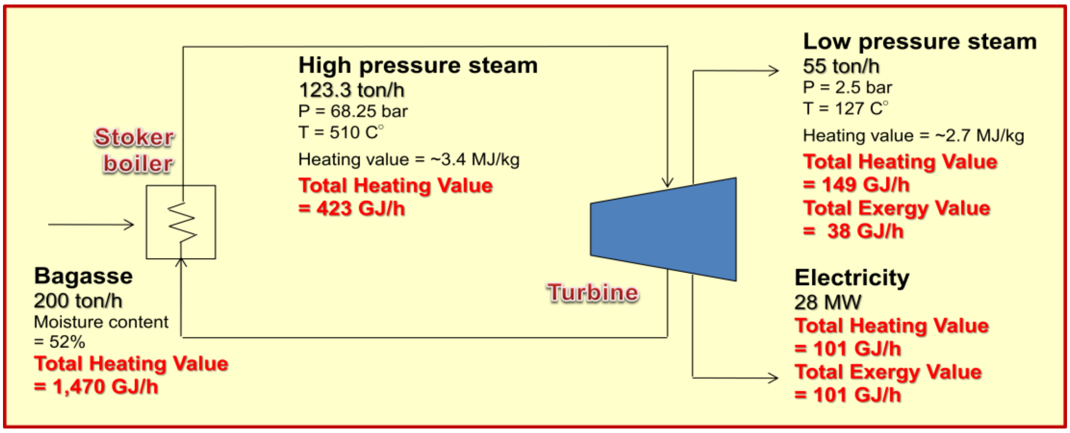

Figure 4. Power plant's cycle heat balance diagram.

5. Conclusions and recommendations

This study has the aim to examine how different are the results from various allocation methods for multi-product processes and to propose a particular one for the sugarcane production system in Thailand. For the standardization and fairness to justify burdens to all products from production processes, the same allocation method must be used if possible.

LCA study of sugarcane biorefinery system by system expansion has limitation since there is no suitable material to substitute products from the process. <MA> is unable to stand alone for this study system since electricity has no physical weight. <MA> for all steps except for electricity and steam replaced by <EA>, <EnA>, and <ExA>, so called hybrid allocation should be avoided to reduce arbitrariness of selecting several available allocation methods. GHG amount of <EA> for this case is not only changeable according to market mechanism but can be also affected by product's price set by parent company's policy with the aim to support sub production units like fertilizer factory. Coincidentally, emission loads to each final product in the case of <EnA> and <ExA> are close to each other for Scheme-a but different for Scheme-b. For the assumed case, that 6.8 kg of remaining steam was all utilized, was raised to distinguish these 2 methods in the Scheme-a. It should be noted that 6.8 kg of low pressure steam produced from turbine generators is considered as waste in Table 1.

Dividing a multifunction process into sub-processes was found to have significant influence on the result. Strictness in choosing either one is difficult since it depends on the situation and definition of selection e.g. from location of site, practice and management, taker of monetary profit, etc. It is recommended to clearly define details of the scheme in the process of objective and scope description. Or else, regarding the environmental evaluation of biomass energy system as sugarcane biorefinery complex, <EnA> is recommended *a priori* due to the correspondence of results for both study schemes (a and b). This is in fact in line with some international initiatives such as the EU's Renewable Energy Directive.

Fertilizer, the last byproduct from every process with none or low economic profit, showed a close range of GHG emissions with electricity in 4 out of 6 study cases because of its high energy and exergy content (due to the high weight of the filter cake). This implied the foresighted decision of owner to realize its value in terms of environment and its importance for soil quality improvement for the long-term sustainability of business.

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