Allocation of Emissions for a Sugarcane Biorefinery Complex in Thailand

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1. Introduction
According to Thailand’s energy policy to promote energy conservation, increasing of biofuels utilization has been targeted not only for attaining energy security and helping alleviate the current economic crisis but also for mitigating global warming problem [1]. In the past, the purpose of sugarcane plantation was mainly to produce food for human consumption. In Thailand, it has now become an important source of biomass energy production such as electricity and ethanol with the hope that this can address the policy targets [2]. Anyways, to produce any other bioproducts, it requires an additional amount of energy and natural resources. To ensure that the effort to acquire such biofuel products really provide benefit, life cycle assessment (LCA) has been used as a tool by many researchers. 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 which can have a huge influence on final results [3]. This study aims to rationally identify a suitable allocation method using a sugarcane biorefinery complex in Thailand as a case study.

2. Methodology
In this study, an attributional LCA approach was used due to its characteristic developed to assess individual processes with several output products [4]. There are a large number of allocation methods for bioenergy systems available in publications [3-5]. The ISO standard for LCA proposes a preference order, the first one being to try and avoid the allocation by substitution method. However, some problems have been encountered from this method. For example, when the considered co-products are actually main products, the result is probably distorted [4]. This as well happens to the case study since each final product is manufactured by independent sub-factory and it is hard to decide which one is main product from the whole process. Allocation of emissions based on mass another recommended by ISO standard will undoubtedly lead to irrational result in this case because one of the product outputs is electricity and it has no physical weight. Another problem is the ethanol, which has a high water content and hence a high mass just due to the water. A hybrid allocation method suggested by the literature with clear evidence that it can serve the aim of providing a reliable result [4] is also avoided here since it, on the contrary, causes individually bias in selecting allocation methods for each stage.

Selected allocation methods of dealing with products from the biorefinery complex in this paper are based on economic, energy and available energy. First two methods are the simple methods for allocation of emissions advised by ISO standard if substitution method and mass-based allocation is inapplicable. Regarding available energy, so called exergy, it is 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 in form of energy has to be produced from its inert reference state. Allocation of emissions based on exergy has recently been applied and recommended for power and steam production system [5]. The study’s research scope also includes the production of electricity and steam as well as production of sugar, fertilizer, and ethanol. System boundary of this paper covers 6 main stages i.e. 1) sugarcane plantation, 2) sugar refinery, 3) molasses-based ethanol factory, 4) power plant, 5) fertilizer factory, and 6) all transportations as shown in Fig S-1 of Supporting Information.

3. Results and discussion
CO2, CH4 and N2O are the environmental emissions considered in this study, expressed as CO2eq as shown in Table S-1 of Supporting Information, to illustrate how much emissions are allocated in each method. Data acquired for the calculation based on real study site in the northeast region of Thailand. The system boundary is particular for a season 2009-2010. Please be noted that the study’s system boundary shown in Fig S-1 is not a closed system since there is bagasse and
molasses input from other nearby factories due to insufficient amount of sugarcane stalk from farmers. In this case, emissions from other factories must be shared to this study system. To simplify the analysis, emission burdens caused by the purchased bagasse and molasses are assumed to have the same values as this study site. Actually, emissions before allocation must equal total emissions after allocation. This means that total emissions for every case of allocation must be equal. Total amount of emissions of this study system is also equal but with respect to additional amount of feedstock from another system and to different allocation methods, total emissions for each basis is then unequal as shown in Table S-1, with the assumption that another sugarcane biorefinery system has the same capacity and release the same amount of emissions. Therefore, total emissions for every case of allocation for these two systems are then equal.

Another observation is the connection between sugar factory and power plant by exchanging bagasse, steam, and electricity. For this operating season (2009-2010), power plant needs to return electricity and steam to sugar factory since lack of bagasse caused by the shortage of cane stalk from plantation section. In this case, share of emissions between these 2 factories is on the basis of converging approach.

As shown in Table S-1, all 3 allocation bases show the close range of results. Economic-based allocation has the advantage to represent the sensible value of each product. As it is sometimes called the market-value-based method, the price of each product can be changed depending upon the market mechanism. For instance, price of ethanol used for calculation in Table S-1 is approximately assumed to be 23 Baht/liter based on the time when the data is collected but it has strong requests in Thailand right now from bioethanol factories to adjust the price to be around 27 Baht/liter. This can change the emission load to ethanol from 17% to 20%. Moreover, prices of products for each country are different resulting in the dissimilar standards to explore environmental burdens while the environmental issue is regularly raised to be discussed at international fora.

Energy-based allocation reveals almost all values close to both economic and exergy-based except for the values of emissions allocated to ethanol. Some studies mentioned on energy-based allocation approach that the burden ratios are valued based on only quantity of energy [5]. This can also be seen from this study for the percentage percentage of total GHG emissions of power plant, by respectively allocating 32% and 68% to electricity and steam. In other words, this ratio means that the value of steam from power plant is justified to be higher than that of electricity on the basis of allocation by energy. Consequently, bigger load allocated to steam from power plant are transferred to sugar factory and proportionately cause the increasing burden of bagasse, an intermediate product from sugar factory. As earlier mentioned, standard to judge the emission load to exported product is same and. The shift of higher load from another system under the concept of allocated emissions is the reason why total emissions of energy-based allocation are rather than that of economic and exergy-based. On the other hand, ratio of emission from power plant of electricity is higher than that of steam, based on both terms of exergy (66/34) and economic (52/48), with more sensible reason. By the scientific way of receiving value for exergy concept, it is therefore stable. This results of this study are thus in line with the literature [5] regarding the allocation of emission based on exergy for life cycle of energy product.

4. Summary
Exergy-based methodologies account for the quality of the outputs of the systems involved, and thus they can remove the arbitrariness. Nevertheless, this rationalization may stand for only this specific case study and just gives the idea as the guideline for further LCA investigation.

5. References
Supporting Information

Fig S-1 System boundary of the research

PEA: provincial electricity authority,

Bagasse* & Molasses* are intermediate product ordered from factories nearby

Table S-1 CO$_{2}$eq emissions shared to products from life cycle based on 3 allocation methods

<table>
<thead>
<tr>
<th>Allocation method</th>
<th>Products from life cycle chain</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sugar</td>
</tr>
<tr>
<td>Energy</td>
<td>144.0</td>
</tr>
<tr>
<td>Exergy</td>
<td>145.1</td>
</tr>
<tr>
<td>Economic</td>
<td>149.0</td>
</tr>
</tbody>
</table>