Life-cycle energy and environmental analysis of bioethanol production from cassava in Thailand

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Abstract

In this study, the life-cycle energy and environmental assessment was conducted for bioethanol production from cassava in Thailand. The scope covered all stages in the life cycle of bioethanol production including cultivating, chip processing, transportation and bioethanol conversion. The input–output data were collected at plantation sites and ethanol plants which included materials usage, energy consumption, and all emissions. From the energy analysis, the results show that cassava-based bioethanol has a negative net energy value with an energy ratio was less than 1, indicating a net energy loss. For the environmental performance, the results show that throughout the life cycle of bioethanol, the conversion stage contributes most to the environmental impacts which is due to the use of coal for power and steam production in the bioethanol plants. It is suggested that a partial substitution of coal with biogas produced from existing wastewater treatment could lead to a significant reduction in the environmental impact.

1. Introduction

At present, Thailand is facing an energy crisis due to high crude oil price and the country's highly dependence on imported petroleum products. Since 2004, the oil price has gradually increased which drives Thai government to promote the development of domestic alternative energy resources for sustainable energy supply. The government has set the National renewable energy plan which aims to increase the use of renewable energy from 0.5% in year 2003 to 8% by the year 2011 (DEDE, 2004). Bioethanol is one of the important alternative energy sources for sustainable energy supply. Thailand is very capable of producing ethanol from biomass, especially bioethanol from cassava and molasses. Nowadays, ethanol is used in Thailand not only as fuel additive for octane enhancement but it is also used to blend with gasoline to produce transportation fuels at various ethanol contents such as E10, E20 and E85. Cassava is an important economy crop of Thailand which is grown mainly in the northeastern area of the country. Recent records have shown that 12 cassava-based ethanol commercial producers have registered with authorities in Thailand with total output capacity of 2.53 million liters of ethanol per day. However, Thailand still lacks of data on the energy performance and environment effect of alternative fuels, especially for bio-derived fuels, which its life-cycle spans through several life stages including cultivation, harvesting, transportation, and conversion. In this perspective, life-cycle assessment or LCA is widely known to be an effective technique to thoroughly and fairly evaluate the environmental impacts of product or process and can appropriately be applied to evaluate alternative fuels or biofuels.

Previous studies evaluated the environmental impacts of bio-based fuels in various categories, including non-renewable energy consumption, greenhouse gas emissions, acidification, eutrophication, human and ecological health, photochemical oxidation, etc., but came up with divergent conclusions, possibly due to different approaches, scope and system boundaries (Kim and Dale, 2002; Hu et al., 2004a,b; von Blottnitz and Curran, 2006; Wang et al., 2007; Nguyen et al., 2007a,b,c; Persson et al., 2009). Most studies have concluded that the use of bioethanol as liquid fuel could reduce greenhouse gas emissions. Hu et al. (2004a) indicated that life-cycle economic, environment and energy assessment provide an important tool for policy makers to better understand trade-offs among economics, environmental impacts and energy for the most effective use of regional energy resources. In another study, Hu et al. (2004b) presented that cassava-based ethanol has a lower net energy, better CO2 emission and lower external cost of CO2, but has higher production cost than conventional gasoline (CG) does, 0.37 MJ/MJ (49% of CG), 72.61 g/MJ (83% of CG), 0.87 and 0.14 RMB/MJ (200% of CG), respectively.
tigated the energy and renewable energy efficiency of cassava fuel ethanol in Guangxi which showed positive net energy and net renewable energy values of 7.475 MJ/L and 7.881 MJ/L, respectively. Leng et al. (2008) concluded that cassava-based ethanol is energy efficient as indicated by an energy output: input ratio of 1.28 and a major contribution to energy consumption and SO2 and CO2 emissions primarily comes from ethanol conversion phase as a result of the combustion of coal to produce energy.

Nguyen et al. (2007a,b) conducted a study on the net energy balance and greenhouse gas (GHG) emissions of ethanol from cassava based on a pilot plant data of the Cassava and Starch Technology Research Unit (CSTRU), Kasetsart University, Thailand and found that the energy balance is positive and net avoided GHG emissions based on a pilot plant data of the Cassava and Starch Technology Research Unit (CSTRU), Kasetsart University, Thailand and found that the energy balance is positive and net avoided GHG emission is 1.6 kg CO2 eq. per liter of ethanol. Yu and Toa (2009) studied an energy efficiency of cassava-based fuel ethanol in China, Guangxi by the Monte Carlo method and showed that the energy balance is a positive net energy and energy input: output ratio of 0.7 MJ/MJ. Several LCA studies indicated that in categories of abiotic depletion, GHG emissions, ozone layer depletion, and photochemical oxidation, bioethanol is better fuel than gasoline whereas gasoline is better in terms of human toxicity, ecotoxicity, acidification and eutrophication (Luo et al., 2009; Kim and Dale, 2008). In addition, they reported that the use of coal as energy source in ethanol conversion phase has negative impact on GHG emissions.

The objectives of this study are to (1) evaluate an energy efficiency of a commercial cassava-based bioethanol production plant in Thailand and (2) to assess the life-cycle environmental impacts associated with the bioethanol production from cassava. The life-cycle inventory analysis and impact assessment were carried out based on ISO 14040 for all stages involved in the production of 1 L of 99.5% ethanol from cassava which included cultivation, chip processing, transportation and bioethanol conversion. Net energy gain (NEG) and net energy ratio (NER) were used as indicators to assess the energy efficiency of the cassava-based ethanol production.

2. Methodology

LCA methodology used in this study was based on ISO 14040 framework, which consists of four steps; goal and scope definition, inventory analysis, impact assessment, and interpretation (Lee and Inaba, 2004).

2.1. Goal and scope definition

The goal of this study is to assess the environmental performance of commercial bioethanol production from cassava based on a life-cycle approach, and estimate the net energy of cassava-based ethanol production in Thailand. The functional unit (FU) of this study is 1 L of 99.5% bioethanol production from cassava as octane improvement fuel. The system boundary is shown in Fig. 1.

2.2. Assumptions and limitations

In this study, most of input–output data were collected as primary data at the actual sites in Thailand including cassava plantation, cassava chip production, and bioethanol production plants. These collected data included raw materials used, energy consumption, utilities, and wastes generated within the system boundary. The secondary data were used in this study as necessary from literatures, calculation, and ecoinvent database for some items such as the production of fertilizers, herbicides, etc.

2.3. Life-cycle inventory analysis

The life-cycle inventory analysis was performed on the material and energy inputs, air emission, waterborne emission, and solid wastes involved in the life cycle of cassava-based bioethanol production based on 1 L of 99.5% bioethanol. Details of each stage are described in the following sections.

2.3.1. Cassava cultivating stage

Major farming activities including land preparing, planting, fertilizing, weeding, and harvesting were covered in this stage. The background data were gathered from various research studies and foreign databases (Pimentel, 1992; Ecoivent, 2006; Nguyen et al., 2007b). Detailed information on fuel, fertilizers, and herbicides inputs was verified by field survey in the northeastern cultivation area of the country. The total cassava planting area in 2007 was 1.2 million hectare and production yield was 22.9 ton fresh roots per hectare. When comparing to India which had 0.24 million hectare of cassava planting areas, the production yield was 31.4 ton fresh roots per hectare which was 37% higher than production yield of Thailand (Office of Agricultural Economics, 2008).

2.3.2. Cassava chip production stage

Major activities included in this stage were chopping, sun drying, and turning chip by tractor. After being harvested, cassava roots are readily converted to dried chips using only simple chopping machine. In this stage, the background data were collected from relevant research study in Thailand (Nguyen et al., 2007a).

2.3.3. Ethanol conversion stage

The processes included in this stage consist of milling, mixing and liquefaction, saccharification, fermentation, distillation, and dehydration. The main product is 99.5% ethanol or anhydrous ethanol. The co-products are CO2, DDGS (Dried Distillers’ Grain with Soluble, a kind of dried animal feed), biogas, and manure. In order to produce 1 L of anhydrous ethanol, approximately 6 kg of fresh roots (25% starch content) or 2.5 kg of dried chips (65% starch content) are required; however, the conversion ratio varies depending on processing efficiency (Sriroth et al., 2000). In this study, data were collected from one present commercial cassava-based ethanol plant in Thailand with a production capacity of 130,000 L a day. This factory employed cogeneration systems to produce both steam and electricity using coal as a fuel which accounts for 90% of total energy consumption. In addition, it purchased electricity from the power grid to fulfill the remaining 10% of total energy consumption. Air emissions from the combustion of coal were calcu-
lated using emission factors from IPCC. For CH₄ emission to the atmosphere from an anaerobic pond treating distillery spent wash was calculated using a default value of 0.6 kg CH₄/kg BOD converted (IPCC, 2006).

2.3.4. Transportation stage

The transportation of fertilizers from foreign countries was calculated using distance from overseas to Thailand in a range of 1000–16,000 km (one-way) depending on the origins with a fuel oil consumption rate of 0.086 MJ/ton km for containership. For domestic transportation within the country, the calculation was based on 10-ton truck (diesel oil consumption of 3.5 km/L) and a shipping distance of 50–100 km (two-way). Air emissions from transportation stage were calculated using emission factors from IPCC (IPCC, 2006).

2.4. Life-cycle energy analysis

2.4.1. Primary energy calculation

Primary energy of diesel oil is a sum of low heating value (LHV) of diesel oil (direct energy use) and the energy required for the diesel production including fuel extraction, refining/conversion and delivery (indirect energy use). LHV of diesel oil (36.4 MJ/L) was obtained from a national study report (TEI, 2001) and energy requirement for producing diesel (8.1 MJ/L) adopted from the Institute of Food and Agricultural Sciences, University of Florida (IFAS, 1991). For electricity grid mixed of Thailand, the energy content plus energy requirement for producing electricity was calculated using distance from overseas to Thailand in a range of 1000–16,000 km (one-way) depending on the origins with a fuel oil consumption rate of 0.086 MJ/tom km for containership. For domestic transportation within the country, the calculation was based on 10-ton truck (diesel oil consumption of 3.5 km/L) and a shipping distance of 50–100 km (two-way). Air emissions from transportation stage were calculated using emission factors from IPCC (IPCC, 2006).

2.4.2. Energy performance estimation

This part aims to assess the life-cycle energy consumption of the bioethanol production including cassava farming and harvesting, cassava chip production, transportation and ethanol conversion. Based on energy input and output for 1 L of 99.5% bioethanol, the Net Energy Ratio (NER) and Net Energy Gain (NEG) can be estimated by Eqs. (1) and (2), respectively (Papong et al., 2008).

\[
NER = \frac{E_{out}}{E_{in}} \quad (1)
\]

\[
NEG = E_{out} - E_{in} \quad (2)
\]

where \(E_{out}\) is an energy output which is the heating value of the fuel ethanol (21.20 MJ/L), \(E_{in}\) is the amount of total primary energy inputs to produce 1 L of ethanol. The NEG is a key indicator to identify whether ethanol production and utilization results in a gain or loss of energy.

2.5. Life-cycle impact assessment

The inventory data from each phase were compiled in SimaPro 7.1 to evaluate the environmental impacts of the cassava-based bioethanol production using the CML 2000 method covering abiotic depletion (ADP), global warming (GWP), ozone layer depletion (ODP), human toxicity (HTP), photochemical oxidation (POCP), acidification (AP), and eutrophication (EP).

3. Results and discussion

3.1. Results from energy analysis

The energy input in the product system was divided into four stages: energy use in cassava cultivating and harvesting, energy use in chip processing, energy use in transportation, and energy use in ethanol conversion stage. The results showed that the production of 1 L of cassava ethanol required the total energy input of 24.92 MJ/L of bioethanol of which the energy usage in the ethanol conversion stage was highest (77.1% of total energy input). The energy usage in cultivating and harvesting stage was the second, accounting for 18.6% which mainly came from the production of chemical fertilizers. The transportation and cassava chip processing stages were shown to consume relatively low energy in the life cycle, 3.2% and 1.2%, respectively. The comparison between the total energy output and energy input showed that NEG and NER of cassava-based ethanol were −3.72 MJ/L and 0.85, respectively. These NER and NEG values indicated a net energy loss and no energy credits from co-products such as manure, biogas, CO₂, and DDGS which have not yet been utilized at present. The energy efficiency ratio would be higher by improving production efficiency and co-products utilization. As cassava-based bioethanol plants usually generate a large amount of wastewater as observed in the study site, the biogas produced from wastewater treatment plant could be utilized for energy production which can reduce coal usage. A study by KAPI/KU (2006) on the co-products utilization of ethanol production showed that CO₂, DDGS, and biogas from cassava ethanol plant are about 734 g CO₂ per FU, 234 g per FU, and 0.113 m³ per FU, respectively. Based on heating value of biogas with 65% CH₄, 22.4 MJ/m³, energy recovered from biogas could be used to substitute coal usage by 10–20% or its energy credit was 1.76–3.45 MJ/FU (Ronjinaridhipched et al., 2003). In addition, DDGS could also be utilized for animal feed production. Based on energy content of DDGS is 20.79 MJ/kg (Kodera, 2007), its energy credit was 4.85 MJ/FU. For CO₂, it could be captured and sold for a low economic value. In this study, CO₂ was released to the atmosphere, however, this CO₂ emission from renewable biomass do not add to the overall atmospheric burden of carbon on a life-cycle basis (Prakash et al., 1998).

However, if co-products (DDGS and biogas) are utilized, the energy inputs were allocated based on the energy content of bioethanol and co-products (Kim and Dale, 2002; Bernesson et al., 2006; Kodera, 2007), which results in 75% and 25% allocated to bioethanol and co-products, respectively. The NEG and NER of the whole life-cycle cassava-based ethanol production are 19.03 MJ/L and 1.11, respectively. This clearly shows an energy profit for the cassava-based ethanol system if they have utilized co-products.

3.2. Sensitivity analysis

In this study, a sensitivity analysis was made to identify the effect of some possible changes on the NEG. Using coal as main source of energy in the ethanol conversion process was treated as the base case; six options were considered in this sensitivity analysis: (1) the influence of increasing and decreasing of cassava yield by 10%, (2) the influence of increasing and decreasing of coal consumption in ethanol conversion by 10%, (3) the substituting 10% of coal input with energy recovered from biogas, (4) the substituting 20% of coal input with energy recovered from biogas, (5) the voided energy credit from DDGS utilization, and (6) combination of decreasing 10% of coal consumption and 10% energy recovered from biogas.

From Fig. 2, we can see that comparing to the base case where NEG is negative (−3.72 MJ/L), options (1), (2), and (3) do not help im-
prove the energy efficiency as their NEG are still negative. For option (1), a 10% increasing in cassava yield results in an 11.0% increase in NEG, whereas an equal decrease would cause an 11.0% decrease in NEG. However, the magnitude of NEG change is relatively small. For option (2), increasing coal consumption in ethanol conversion by 10% reduces NEG by 1.5 MJ/L ethanol, whereas 10% decrease in amount of coal used results in increasing energy efficiency by only 10%. For option (3), if energy recovered from biogas in the conversion process is used to replace 10% of coal, this has a positive effect on NEG but the energy saving is only about 1.5 MJ/L ethanol. It is very interesting to see from this figure that the NEG changes from negative to positive with options (4), (5), and (6). These options would result in energy saving more than 3.72 MJ/L ethanol, and thus, causing the NEG to turn from negative to positive value. The analysis results shown in this figure can be used as a guideline to select options for improvement in using energy resources efficiently and type of energy resource appropriately. It is suggested that the utilization of co-products (such as biogas and DDGS) significantly increases cassava-based bioethanol’s energy benefits.

3.3. Results from inventory analysis

The results of the cradle-to-gate inventory for the key environmental flows are presented in Table 1. Depletion of non-renewable resources is an important criterion to decision making on alternative fuels. For the study site, coal usages are highest in ethanol conversion stage which also results in airborne emissions due to coal burning in this process. Furthermore, water pollution is attributed mainly to the treatment of wastewater from the ethanol production which also results in CH4 emissions as discussed earlier. For cassava farming and harvesting stage, significant effects observed were from the production of chemical fertilizers extensively used in the cultivation stage as shown in Fig. 4.

3.4. Results from impact assessment

The life-cycle environmental impact assessment covering cultivation and harvesting, cassava chip production, transportation and conversion of bioethanol production from cassava showed that the ethanol conversion stage had the highest environmental impact in almost all impact categories such as abiotic depletion, global warming or greenhouse gas (GHG), photochemical oxidation, human toxicity and eutrophication, except ozone layer depletion and acidification categories as shown in Fig. 3. This can be attributed to the use of coal for power and steam production during the conversion process and wastewater generated in this process as well as CH4 emission as discussed earlier. For cassava farming and harvesting stage, significant effects observed were from the production of chemical fertilizers extensively used in the cultivation stage as shown in Fig. 4.

Focusing on the ethanol conversion stage, the further analysis could be done as shown in Fig. 5. The results showed that major
environmental impact caused from utilization of coal as fuel and the emission from the process. This is due to the fact that coal is non-renewable resource and burning coal generates CO₂, SOₓ, and NOₓ more than other fuels which contribute to the global warming, acidification, human toxicity and abiotic depletion. Besides coal usage, the bioethanol production processes also used a large amount of water, nearly 10 times of the product volume, resulting in wastewater and methane which have impact on global warming, photochemical oxidation and eutrophication category. Thus, attempts on reduction of the environmental impacts should be made in the conversion stage which could be an increase in the use of alternative and more environmental friendly energy such as biogas from the wastewater treatment system to reduce the use of coal.

For the life-cycle GHG emissions, in the case where co-products (biogas and DDGS) have not yet been utilized, the results showed that coal used as fuel and methane emission from wastewater treatment process contributed most in this impact category, accounting for 43.4% and 38.6% of total 2.86 kg CO₂ eq. per FU, respectively. Other contributions were from electricity used in ethanol plant, utilization of chemical fertilizer in cultivation and emission from N-fertilizer application, respectively, as shown in Table 2. In the case where co-products are utilized, the environmental emissions (GHG emissions) were allocated based on the energy content of bioethanol and co-products (Kim and Dale, 2002; Bernesson et al., 2006; Kodera, 2007). The results after allocation are also shown in Table 2 for comparison. From this table, it can be seen that utilization of co-products such as the use of DDGS for animal feed and the use of biogas (90% captures) for producing power and steam has shown to be much better for the environment than coal combustion. Thus, energy recovered from biogas generated from the anaerobic digestion of the spent wash can be advantageous to the conversion process. These options would bring about 50% decrease in GHG emissions.

Table 2
Life-cycle GHG emission of 1 L anhydrous ethanol production.

<table>
<thead>
<tr>
<th>Items contribution</th>
<th>Ethanol (without allocation)</th>
<th>Ethanol (with 25% allocated to co-products)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g CO₂ eq. per L</td>
<td>%</td>
</tr>
<tr>
<td>Coal combustion</td>
<td>1243</td>
<td>43.4</td>
</tr>
<tr>
<td>CH₄ from ethanol wastewater treatment</td>
<td>1104</td>
<td>38.6</td>
</tr>
<tr>
<td>Electricity</td>
<td>186</td>
<td>6.5</td>
</tr>
<tr>
<td>Fertilizers</td>
<td>182</td>
<td>6.4</td>
</tr>
<tr>
<td>Transport</td>
<td>62</td>
<td>2.2</td>
</tr>
<tr>
<td>N-Fertilizer emission</td>
<td>52</td>
<td>1.8</td>
</tr>
<tr>
<td>Cassava chip production</td>
<td>17</td>
<td>0.6</td>
</tr>
<tr>
<td>Herbicides</td>
<td>7</td>
<td>0.2</td>
</tr>
<tr>
<td>Diesel in cultivation</td>
<td>6</td>
<td>0.2</td>
</tr>
<tr>
<td>Chemical in ethanol conversion</td>
<td>4</td>
<td>0.1</td>
</tr>
<tr>
<td>Total</td>
<td>2863</td>
<td>100</td>
</tr>
</tbody>
</table>
3.5 Improvement of the environmental performance

From the results, possible and practical improvements could be made in order to decrease CO₂, CH₄, SO₂, and NOₓ emissions by using steam more effectively and utilizing co-products such as biogas generated from the wastewater treatment plant as a partial substitution for coal. This is not only enhancing energy self-sufficiency through biogas recovery from anaerobic digestion pond but also improving the GHG balance through abatement of CH₄ emission from the anaerobic pond and CO₂ emission from coal combustion. For the improvement in the environmental performance, three scenarios have been analyzed in this study as follows: (1) the partial substitution (20%) of total coal used by biogas (85% boiler efficiency), (2) the energy credit from DDGS utilization (as animal feed), and (3) the 10% decreasing of coal usage (improving energy efficiency in cassava conversion process) and 10% energy recovered from biogas (90% capture and 85% boiler efficiency). The improvement analysis is shown in Fig. 6. It can be seen that a partial substitution of biogas recovered from spent wash for 20% of total coal used (option 1) could result in 42.6% GHG reduction compared to base case whereas options 2 and 3 would reduce the GHG emission by 22.1% and 23.6%, respectively. In term of photochemical oxidation (POCP) category, option 1 could reduce 69.0% compared to base case while options 2 and 3 would reduce this impact by 19.0% and 24.0%, respectively. The results show that the magnitude of GHG and POCP change is relatively significant as a result of CH₄ reduction, whereas the effect was not significant in other categories.

3.6 Uncertainty

As the life-cycle energy and environmental performance presented in this paper are based on data collected from various sources, it is important to take into consideration the source, magnitude and impact of uncertainties as listed in Table 3. A 'low' impact does not lead to significant changes in the conclusions. A 'medium' impact denotes something that is noticeable in energy efficiency or environmental impact, but the general conclusions of the previous sections still hold. A 'high' impact has the potential to invalidate major conclusions. In this study, unfortunately we are dealing with all three levels of impact from uncertainties. For low impact type, we have carefully chosen the set of data that we consider most accurate and best represent for that category. For medium and high impact types, since they are beyond our capability to control or manage, we have included them in the sensitivity analysis.

4 Conclusions

In the present study, we have performed the life-cycle energy and environmental evaluation for cassava-based bioethanol production. The NEG and NER values of cassava-based ethanol are found to be -3.72 MJ/L and 0.85, respectively. Major energy consumption comes from the ethanol conversion stage which accounts for 78% of the total energy usage. This ethanol production/conversion stage has shown to contribute most to the environmental impact when compared with other stages. It is a result of the use of coal and coal combustion for the production of power and steam used in the process. This effect could possibly be reduced by the use of biogas recovered from wastewater treatment. To increase NEG and reduce the environmental impact, it is suggested that partial substituting of coal with biogas to produce power and steam needed for ethanol production as well as reduction in use of fertilizers in plantation stage should be done.

Acknowledgements

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References


Kodera, K., 2007. Analysis of Allocation Methods of Bioethanol LCA. Center of Environmental Science (CML), Leiden University, Amsterdam.


Table 3

<table>
<thead>
<tr>
<th>Cause (type of uncertainty)</th>
<th>Magnitude (%)</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variations in the upstream emissions and energy requirement of cassava cultivation (variability)</td>
<td>±2 to ±5</td>
<td>Low (medium if above 5%)</td>
</tr>
<tr>
<td>Variations in feedstock properties because production methods of biomass and coal vary (variability)</td>
<td>0 to ±20</td>
<td>Medium, affects efficiency</td>
</tr>
<tr>
<td>Variation in the conversion performance of plant components such as fermentation reactor, distillation column (lack of data)</td>
<td>±5 to ±10</td>
<td>Medium, also depends on practice</td>
</tr>
<tr>
<td>Variation in co-products (such as DDGS and biogas) utilization (variability, not common, or developing)</td>
<td>0 to 30</td>
<td>High, affects viability</td>
</tr>
<tr>
<td>Differences in the actual logistical and transport situation</td>
<td>-1 to +1</td>
<td>Low</td>
</tr>
</tbody>
</table>

Sources and magnitude of uncertainty in the data and impact on results.


