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Energy balance and GHG-abatement cost of cassava utilization for fuel ethanol in Thailand

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Abstract

Since 2001, in order to enhance ethanol's cost competitiveness with gasoline, the Thai government has approved the exemption of excise tax imposed on ethanol, controlling the retail price of gasohol (a mixture of ethanol and gasoline at a ratio of 1:9) to be less than that of octane 95 gasoline, within a range not exceeding 1.5 baht a litre. The policy to promote ethanol for transport is being supported by its positive effects on energy security and climate change mitigation. An analysis of energy, greenhouse gas (GHG) balances and GHG abatement cost was done to evaluate fuel ethanol produced from cassava in Thailand. Positive energy balance of 22.4 MJ/L and net avoided GHG emission of 1.6 kg CO_2 eq./L found for cassava-based ethanol (CE) proved that it would be a good substitute for gasoline, effective in fossil energy saving and GHG reduction. With a GHG abatement cost of US\$99 per tonne of CO_2, CE is rather less cost effective than the many other climate strategies relevant to Thailand in the short term. Opportunities for improvements are discussed to make CE a reasonable option for national climate policy.

Keywords: Cassava ethanol (CE); GHG abatement cost; Life cycle assessment (LCA)

1. Introduction

The Thai economic recovery after the Asian financial crisis has brought with it rising concerns about the country's environment. In the same context as other countries in the region, Thailand's fossil-based energy consumption and, consequently, carbon emissions per unit of GDP have been on the rise since 1990. Estimated from fossil fuel consumption, CO_2 emissions from the Thai transport sector in 1999 accounted for 33% of the total national annual CO_2 emissions (Earth trends, 2003).

In fact, as a non-Annex I country under the Kyoto Protocol, Thailand does not have binding obligations to limit or reduce GHG emissions. However, concerned with the event of rising sea level in low-lying coastal regions of the country most likely associated with greenhouse effect, the Thai government ratified the agreement in August 2002.

Since the basic goal of climate policy is to reduce CO_2 emissions from the extensive use of fossil-based energy, there exists a close link between climate policy and energy policy. As for Thailand, the *Asia Least-cost Greenhouse Gas Abatement Strategy* study conducted by Asian Development Bank (ADB) has identified the mitigation options in the energy sectors that contribute significantly to GHG reduction. These mitigation options are categorized into three items, improving efficiency of energy-related processes, adopting more energy-efficient techniques and substituting renewable energy for fossil-based energy resources (ADB, 1998). In the short term, the following options were found to provide not only mitigation potential but also economic benefits, indicated by their negative GHG abatement costs, ranging from US\$8.3 to US\$323.1/tonne CO_2 eq.: (1) cogeneration, increase in oil-fired boiler efficiency, and application of efficient motors in industrial sector; (2) refrigerator program in residential sector; (3) lighting and air conditioner efficiency program in residential and commercial sectors, and (4) increase in fuel economy of automobiles. Utilizing or switching to

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cleaner fuels, i.e., from coal to natural gas, from natural gas to nuclear, and more electricity generation from nuclear is also attractive at positive abatement costs of US$1.2 to US$69.6/tonne CO_2 eq. As a whole, there are 13 options making a list of cost-effective GHG mitigation options for Thailand, starting from US$323.1/t CO_2 at the top to US$69.6/t CO_2 at the bottom. Though renewable energy resources did not appear in the list, their high potentials in reducing CO_2 emissions were highlighted. In Thailand, several renewable energy projects that are strong CDM (Clean Development Mechanism) candidates are going on. The strongest are clean Independent Power Producer (IPP) projects which are designed to use biomass to produce electricity (Todoc, 2004).

Apart from the direct combustion of biomass for energy production, extensive studies have been carried out in recent years to investigate the potential to convert biomass to liquid fuels, substituting for gasoline and diesel in transportation. One of the most important biomass-derived liquid fuels is ethanol. The first trials to use ethanol for fuel in Thailand actually commenced in the early 1977s, but its high cost over that of gasoline halted commercial production. However, at present, given the continually increasing oil prices and increasing public concern about climate change due to vast amount of CO_2 emitted from various transport facilities, ethanol is being reconsidered as a potential alternative to gasoline.

In Thailand, three types of raw materials regarded as having high potential for ethanol production are sugar cane, cane molasses and cassava. However, the most suitable one is cassava (Sriroth et al., 2003). The major advantages of cassava over molasses and sugar cane can be listed as follows:

(1) Cassava is well known as a hardy crop having the ability to adapt well to a wide range of growing conditions with minimal inputs. In Thailand, cassava ranks the third most important cash crop after rice and sugar cane. Various institutions/research centers have conducted cassava improvement research and made the research results relevant to farmers' real conditions, ensuring adaptation as well as adoption by farmers. Due to the introduction of high-yield varieties and improved production practices, an increase in national cassava yield from 13 t/ha in 1995 to 20 t/ha in 2004 was recorded (OAE, 2004).
(2) Unlike sugar-based distilleries that are operated seasonally, cassava-based ethanol industry can be put in operation continuously, thanks to the crop's unbound time window for growing and harvesting, plus its capability to be stored as dried chips.
(3) The inadequate Thai cane productivity (60 Mt/yr) compared to sugar mill capacity (75 Mt/yr) implies that very limited surplus stock of sugar cane is available for ethanol production (DEDE, 2004c). The complication of sugar cane and sugar legislation on profit sharing between farmers and millers adds one more disadvantage of sugar cane utilization for ethanol production. With molasses, high demands in both domestic and international market have resulted in supply shortage and, consequently, strong fluctuation in price. In contrast, there is frequently an oversupply of cassava leading to falling prices and incomes for farmers. The ethanol industry once developed would provide a partial solution to the problem. Regarding supply potentials, of the total 20 Mt of the annual production of cassava in Thailand, approximately 40% is absorbed by starch industry and another 40% is processed to chips and pellets, mainly for export. The surplus 20% is utilized mainly for low-end applications such as domestic animal feed (CSTRU, 2004). It is reasonable to convert this surplus to 2 million litres (ML) of ethanol per day, ensuring a stable source of feedstock and a neutral impact on starch and chip/pellet industries.
(4) Technical development in ethanol conversion from grains available elsewhere in the world can be readily applied to cassava. This would help to boost input energy efficiency and reduce production cost.

According to the government plan, by 2007 and 2008, the number of cassava-based ethanol (CE) plants in Thailand would amount to 12 with the total output of about 3.4 ML per day (Sukphisal, 2005). The strategic plan for cassava needs to be revised and reformulated to meet additional demand for ethanol fuel. A decrease in the export of cassava products is mostly a short-term solution. Long-term strategy set up by national cassava policy is improved crop productivity from an unchanged planted area of 1.06 million hectares. It can be achieved by the dissemination of good stake of new varieties and better cultivation/harvest practice. From a current yield of about 19 t/ha, by 2007, the root yield is projected to reach 31 t/ha for a promoted area of about 192,000 ha and 21 t/ha for the rest. The promotion of contract farming is another measure to support ethanol project (Sriroth et al., 2006).

Whilst studies carried out in a diverse group of countries around the world, e.g., Brazil, the US, Canada, show that ethanol produced from sugar cane and corn can help reduce oil import and GHG emissions (Macedo et al., 2004; Wang et al., 1997; Levelton, 2000), there remains an uncertainty whether ethanol from cassava could provide the same benefits in Thailand. A satisfying conclusion cannot be reached unless an analysis of energy and GHG impacts of the use of CE as a substitute for conventional gasoline (CG) in the country is conducted.

To assess the contribution of CE to energy security and climate change mitigation, it is necessary to determine its energy balance (EnB), GHG balance and cost effectiveness in terms of GHG reduction. EnB compares the energy inputs in the production of CG that are avoided when ethanol is used instead of CG to the total fossil energy inputs in the production of ethanol. A positive EnB can be translated into net fossil energy savings whereas a negative

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value reflects an overall energy drain. GHG balance computes net avoided GHG emissions when CG is displaced by ethanol. The cost effectiveness of a biofuel for reducing GHG emissions is defined as the excess cost of the biofuel over that of the conventional fuel it replaces, divided by the GHG reduction that is achieved with the replacement. Since ethanol is not the only measure for reducing GHG emissions, this cost should be compared with that of other alternative climate change mitigation strategies to see whether it is an economically viable option for climate policy.

Thailand has embarked on an ambitious program to promote the use of ethanol (in the form of gasohol) as a transportation fuel. Government's ethanol policies include excise tax exemption for the fuel and income tax waiver for interested investors. However, a shortage of ethanol supply currently has resulted in unpredicted high prices. Ever since gasohol was announced to replace 95 octane gasoline (ULG 95) by 2007, the price of molasses-based ethanol has risen drastically, from Bt19 in January 2006 to Bt25.3 in June 2006 (Thongrung, 2006). Looking for a cheaper and possibly more stable source of such a gasoline substitute, Thai oil companies expect they can get ethanol produced from cassava at a lower cost of about Bt22 a litre (Thongrung, 2006). In comparison, the average ex-refinery price of ULG 95 posted at www.eppo.go.th/info/T12.html in the first seven months of 2006 is Bt18.98 a litre. Thus, in the short term, it seems that CE still cannot compete with CG without government subsidies. The subsidies would, however, be advocated with some economic rationales, of which reasonable GHG-abatement costs of ethanol has been widely addressed. Practically, to be a reasonable substitute for CG, ethanol must meet two criteria. First, the production and use of ethanol should result in a positive EnB and, consequently, a not reduction in GHG emissions. Second, if substituting ethanol for CG does provide GHG emission reduction, the cost of such reduction should be preferably not exceeding the range of cost-effective GHG mitigation options for Thailand (ADB, 1998), i.e., not more than US$69.6/t CO_2 equivalent.

2. Methodology

2.1. Goal and scope definition

The goals of this paper are (1) to estimate energy and GHG balances of CE in Thailand, based on an LCA approach, and (2) to evaluate whether a substitution of CG by CE in Thailand would be a good GHG reduction strategy from an economic perspective.

2.2. Cassava ethanol life cycle: system boundary and data sources

An assessment of life cycle energy and GHG emission implications of CE produced in Thailand, in comparison with CG, was conducted. As shown in Fig. 1, this cycle includes feedstock recovery, transport to the conversion site, conversion to fuel, transport to refueling stations and final combustion in vehicles. The major segments included within the system boundary are cassava farming/processing, ethanol conversion, transportation, and ethanol combustion.

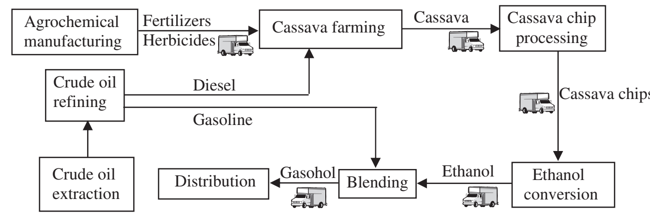

Fig. 1. Life cycle scheme for the studied system.

a. *Cassava farming/processing*: This segment represents all activities related to the production of ethanol's raw materials, i.e., in this case, cassava chips. It starts with cassava farming and ends with chip processing.
   - *Cassava farming*: Steps involved at this stage include land preparation, planting, crop maintenance (fertilization, weed control), and harvesting. Background information on this sub-segment was obtained from ample sources of the country's cassava research (Howeler, 2000; Sriroth et al., 2000; Tongglum et al., 2000; Hershey and Howeler, 2000). Detailed information on fuel, labor and material inputs was reviewed from available references and verified based on on-site data collection.
   - *Chip processing*: After harvest, roots are transported to drying floors which are equipped with simple facilities. Though roots are dried naturally by sunlight, some fuel is consumed for tractor loading roots into chopping machine, for chopping machine itself and for tractor turning over chips during drying period. Also human labor is consumed for chip packing once drying process is completed. Relevant data on fuel consumption and human labor intensity were collected through personal interview with the manager of a typical cassava-drying floor in Thailand (Witriyatornpan, 2006).

b. *Ethanol conversion*: About 20–30 years ago, the production of ethanol from cassava on an industrial scale in Thailand seemed impractical but now, thanks to advanced techniques in biochemical and chemical engineering, the potential is bright. To demonstrate the feasibility of feedstock conversion to ethanol on a commercial scale, a research team in Cassava and Starch Technology Research Unit (CSTRU), Bangkok, Thailand has conducted research on pilot-scale production of ethanol from cassava. The detailed energy use rates for pilot plant were recorded by the research team. The team also made an estimate for commercial production of 100,000 L ethanol a day. The information obtained from the team's research report (Ronjnaridpiched et al., 2003) was used in the study.

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The process of making ethanol from cassava, a starch-based feedstock, consists of three main sub-processes: milling and liquefaction, fermentation, and distillation. After distillation, the non-fermentable solids remaining in distilled mash, termed stillage, are digested to produce biogas. This biogas supports energy in the form of steam used in CE conversion process, substituting a portion of bunker oil, which is the major energy supply for the process. Electricity obtained from the grid is another form of energy supply. In fact, there are potentials of utilization of various by-products associated with ethanol production, e.g., CO_2, fodder yeast, and distillers dried grains with solubles. However, since the CE conversion stage examined was at the pilot scale, and sufficient markets for such products in Thailand have not yet been developed, this study counted these by-products as valueless by allocating all energy inputs and emissions to the CE fuel product itself.

c. *Transportation*: All materials and products involved in the system are hauled by different transport facilities through different distances. Data were collected in one of two ways: (1) information exchange via personal interviews, and (2) educated assumptions/estimations.
d. *Ethanol combustion*: Data related to gasohol E10 were obtained from Tantithumpoosit (2004).

3. Cassava-based ethanol case study

Of the 12 CE plants approved for construction by the Thai government, three are to be located in the Eastern Region of the country with a total daily capacity of 1.6 ML. There are at least three reasons why the region is set up to contribute nearly 50% of the national CE production target. First, it is the country's second-largest cassava producer after the Northeast (OAE, 2004). Following ethanol conversion in the fuel production process is blending ethanol with CG to make gasohol; in Thailand, this is carried out in oil refineries. There are six oil refineries located in the region; fuel saving in transportation of ethanol to oil refineries is the second reason of site selection. Last but not least, good transportation infrastructure plus public utilities due to the presence of major industrial estates here are important criteria supporting the approval of a commercial ethanol industry.

3.1. Direct energy and material inputs

Direct energy and material inputs in the CE fuel system include diesel, bunker oil, chemicals (herbicide, fertilizers), labor work and solar energy.

- *Diesel*: Diesel fuel is used for land preparation, crop maintenance, harvesting and chip processing. It is also the sole fuel used for transportation.
- *Bunker oil*: An inexpensive and fairly available source of energy, bunker oil is burnt in boilers to generate steam utilized for ethanol conversion process.
- *Fertilizers*: Commercial NPK fertilizers and chicken manure are the two types of materials cassava farmers use to enrich soil nutrients. In fact, chicken manure helps to improve the soil's physical condition rather than to supply nutrient elements. As documented in reference (Howeler, 2000), animal manures contain quite low and variable amounts of N, P, K, compared to commercial fertilizers. High application rates necessary to compensate for manures' low macronutrient contents have limited their use in those areas where local supplies are not available.
- *Herbicide*: Herbicide application to control weeds in cassava cultivation is considered simpler than any other method, e.g., hand weeding or mechanical control. Common herbicides used by Thai cassava farmers to suppress weeds are paraquat and glyphosate.
- *Labor work*: Human labor is used in almost every step in cassava farming and processing, e.g., planting, weeding, fertilizer and herbicide application, harvesting and loading, and chip packing.
- *Solar energy*: This energy is absorbed by cassava plants through photosynthesis process and fresh cassava chips during drying process. However, considered free, it was not taken into account in the analysis.

3.2. Energy balance

3.2.1. Primary energy consumption estimation

To assess energy balance of ethanol, it is of importance for primary energy values to be accounted for in the calculation. By definition, primary energy is an aggregation of fuel energy content plus the energy embodied in the process of fuel extraction, refining, production and delivery.

(a) For diesel and bunker oil used in the CE fuel system, fuel energy content values were obtained from the LCI study of oil refineries in Thailand (TEI, 2001). Input efficiency coefficients of fossil energy sources, derived from Institute of Food and Agricultural Sciences, University of Florida (IFAS, 1991), were then used to estimate fuel primary energy values.
(b) For electricity used in ethanol conversion, the factor of 10 was used to convert one kWh electrical energy consumption to MJ thermal energy consumption equivalent. The conversion took into account the Thai average MJ losses during electricity generation of about 64%, estimated based on available reference (DEDE, 2004a) documenting the relative share of fuel sources for electricity generation in Thailand. The information contained in the reference was also useful in estimating the contributions of non-renewable and renewable energy sources to this energy input.
(c) In Thailand, a large portion of chemical fertilizers is imported from abroad. Data on energy use and fuel shares for NPK fertilizer and herbicide manufacturing, packaging, marketing and distribution were adapted

from well-known models and databases (Wang, 2006; Helsel, 1992).

(d) Evaluating the energy equivalent of agricultural labor which was further included as an energy input in cassava farming energy analysis was based on the Life-Style Support Energy (LSSE) method recommended by Odum (Odum,1983). According to Odum, human labor's energy content can be estimated by multiplying its cost by the average energy to monetary unit ratio or energy intensity of the economy. Using available data on (1) total primary energy supply (DEDE, 2004b), (2) GNP of the Thai economy (National Economic and Social Development Board (NESDB), 2005) and (3) the minimum wage in Thailand (FAS-USDA, 2005), the energy value of agricultural labor in Thailand was derived as 12.1 MJ/h. The value is compatible with Fluck's (1992) estimate of about 100 MJ/day or 12.5 MJ/h (assuming 8 h per working day) for semi-industrialized economies, adjusted from 594 MJ/day for agricultural labor in the US. A developing country, Thailand has been in a transition period, moving from a traditional agricultural-based economy into a semi-industrialized economy (JICA, 2003). Another reference value is 13 MJ/h, which was derived by Freedman (1982) for rice production in the developing world.

The energy input in this category was then segregated into fossil and non-fossil energy items, based on Thailand's primary energy consumption by fuel sources. Data were obtained from International Energy Agency energy statistics (IEA, 2005).

3.2.2. Energy balance (EnB)

One of the most important instruments to assess ethanol's fuel value is the "net energy balance". Conventionally, it is a comparison between the heat content of ethanol and the total fossil energy inputs in the fuel production cycle (Levelton, 2000; Shapouri et al., 2004; Macedo et al., 2004; Dai et al., 2006). The key implication addressed is whether ethanol production and use results in a gain loss of energy. However, it cannot answer the question whether a substitution of ethanol for gasoline in transportation can contribute to fossil energy savings. To evaluate this potential, a better instrument is a comparative energy balance (EnB) as defined by Henke et al. (2005). In a comparative EnB analysis, first, a substitution ratio between ethanol and CG needs to be identified. Based on this ratio, the next step is to compare the amount of fossil energy inputs in the ethanol production cycle with the fossil energy used to manufacture CG (including feedstock) which is avoided if ethanol is used to substitute for CG. In estimating the energy balance of bio-ethanol produced in Germany, Henke et al. (2005) derived the substitution ratio between ethanol and CG as 0.65 which is the ratio of the two fuels' energy content.

Although ethanol has fewer megajoules per litre than CG, its higher octane value allows higher compression ratios and more efficient thermodynamic operation in internal combustion engines. In other words, the heating value of ethanol is not a straightforward indicator of its performance in a motor vehicle. PTT Research and Technology Institute, Thailand has conducted tests for various car models running on CG (ULG95) and gasohol E10 (Toyota 1.3 L/1993, Toyota 1.5 L/1996, Toyota 1.6 L/2000, Nissan 2.0 L/1994, Mitsubishi 1.5 L/1994, Volvo 2.3 L/1995, Honda 1.6 L/1996). The fuel economy test results show a difference between ULG95 and gasohol in the range of −1.1% for Toyota 1.6 L/2000 to +1.7% for Toyota 1.3 L/1993 (Tantithumpoosit, 2004). For a conservative estimate assigned to ethanol, this study selected the test results based on Toyota 1.6 L/2000, the newest car model in the test group. The average fuel economy of this car model running on CG and gasohol is 13.46 km per litre and 13.31 km per litre, respectively. Fuel economy comparison reveals that 1 L of gasohol is equal to 0.989 L of CG. The difference of 0.011 L is due to 10% of ethanol in CG. The substitution ratio between ethanol (in E10 form) and CG in a motor vehicle engine was thus derived by this study as 1:0.89 based on fuel economy, instead of 1:0.65 based on energy content.

The energy expended once CG is consumed includes the energy consumed in the production process and the energy contained in crude oil feedstock. The first CG energy component as per definition above was obtained by subtracting the energy content of CG (31.5 MJ/L) from its primary energy value estimated by the procedure described in Section 3.2.1a (38.5 MJ/L). Given a basic mass balance performed for oil refining in Thailand (TEI, 2001), the energy contained in crude oil that is transformed to energy content of CG was estimated as 31.7 MJ/L. The resulting fossil energy sequestered in CG, 38.7 MJ/L, multiplied by the substitution ratio between ethanol and CG, 0.89, yields the reference value of 34.4 MJ/L. This figure was used to compare with the amount of fossil energy inputs in the CE production cycle.

3.3. GHG balance

3.3.1. GHG emissions due to the use of fossil fuels (direct and indirect)

(a) For diesel and bunker oil used in the CE system, both direct GHG emissions, i.e., emissions from fuel combustion, and indirect emissions, i.e., emissions from oil extraction, transportation to oil refinery, refining and transportation to gas station, were taken into account in the analysis. Emission data for petroleum-based fuel cycles were obtained from GREET 1.7 (Wang, 2006).

(b) For electricity used in ethanol conversion segment, GHG emissions were estimated using LCI data for Thailand's electricity grid mix (Lohsomboon and Jirajariyavech, 2003).

(c) Commercial fertilizers and herbicides used in cassava crop maintenance are important sources of GHG emissions via fossil fuel consumption in their manufacturing. To estimate GHG emissions in this category, emission factors (EFs) for their production were taken from GREET 1.7 (Wang, 2006).

(d) Assessing human labor based on "LSSE" method leads to a GHG balance analysis considering emissions associated with fossil fuel consumed to support labor energy. This category emissions were estimated by multiplying the value of fossil energy consumed to support human labor (described in Section 3.2.1d) by the ratio of total national GHG emissions (ONEP-MONRE, 2005) to total national fossil energy consumption (DEDE, 2004b).

3.3.2. Other GHG emissions

This category includes (a) N_2O soil emissions from *N*-fertilizers applied in cassava farming, (b) CH_4 and N_2O emissions from biogas burning, and (c) CH_4 and N_2O emissions from ethanol combustion in vehicles.

(a) N_2O soil emissions depend on a number of factors: (1) environmental factors, e.g., climate, soil organic C content, soil texture, drainage, soil pH and types of receiving water body; (2) management-related factors, e.g., *N* application rate per fertilizer type, types of crop, and (3) factors related to the measurements, e.g., length of measurement period, frequency of measurements (Bouwman et al., 2002). Based on results of numerous studies investigating fertilizer-induced N_2O emissions from cornfields, Wang (1999) derived an emission rate of 1.5% (in weight N/N).

(b) CO_2 emissions from biogas combustion are net zero. CH_4 and N_2O emissions were estimated using EFs from the National Environmental Research Institute, Denmark (DMU-NERI, 2006).

(c) Also, bio-based CO_2 emissions from ethanol combustion are net zero. For CH_4 and N_2O, emission information was obtained from GREET 1.7 (Wang, 2006).

3.3.3. Avoided emissions

GHG emissions are avoided by the use of ethanol as a gasoline substitute in transportation. To calculate gross avoided emissions when ethanol substitutes for CG at a ratio of 0.89 (see Section 3.2.2), fuel-cycle CO_2 emissions from CG cars were estimated from GREET 1.7 (Wang, 2006). According to the model, there is no difference in CH_4 and N_2O emissions between cars fueled with gasohol E10 and those with CG. As a result, only CH_4 and N_2O emissions from feedstock production and fuel conversion stages were considered in avoided emissions accounting. Net avoided emissions were then identified by subtracting total CE life cycle GHG emissions from the resulting gross avoided emissions.

3.4. GHG abatement costs

Ethanol ex-distillery price or gate price represents production cost plus distillery profit margin. Before being distributed to gas stations, ethanol is transported to oil refineries for blending with CG. At gas stations, the retail price of ethanol in the form of gasohol is formulated as: retail price = ex-refinery price + oil fund + taxes + marketing margin + VAT (EPPO, 2006), in which ex-refinery price is a sum of gate price and transportation/distribution cost. As mentioned earlier, to encourage consumers to use gasohol, the Thai government provides fuel subsidies and tax incentives that make gasohol 1.5 baht-a-litre cheaper than ULG 95. A fair comparison between ethanol and CG should be based on their ex-refinery prices rather than retail prices. To derive the price per gasoline-equivalent litre, ethanol ex-refinery price per litre is divided by 0.89 which is the substitution ratio of the performance between ethanol (in the form of E10) and CG in an explosion motor.

4. Results

4.1. Energy balance

Table 1 shows that the production of 1 L of CE substituting for 0.89 litre of CG would result in energy savings of 22.38 MJ which corresponds to about 0.58 L of CG. The estimate shows that, with a daily production capacity of 3.4 ML of CE substituting for CG in transportation, Thailand could save totally about 720 ML of CG per year. Looking further at energy consumption by segments, one can see that among all segments involved in the CE system, the ethanol conversion is the most energy-consuming one, dominating at 55.5% of the total fossil energy inputs. Following are the cassava cultivation/processing and transportation contributing 32.4% and 12.1%, respectively (Fig. 2). Human labor energy accounts for almost 29% of fossil energy requirement in feedstock

Table 1
Energy balance of cassava-based fuel ethanol

Items	Fossil energy inputs (MJ/L ethanol)	Non-fossil energy inputs (MJ/L ethanol)
Feedstock production	*3.91*	*0.32*
Fertilizers, herbicide	1.68	0.08
Diesel fuel	1.09	0
Labor	1.14	0.24
Ethanol conversion	*6.69*	*0.01*
Thermal energy (steam)	6.36	3.45
Electricity	0.33	0.01
Biogas cogeneration		−3.45
Transport (diesel fuel)	*1.46*	*0*
Total	*12.06*	*0.33*
EnB	*34.4−12.06 = 22.38*	

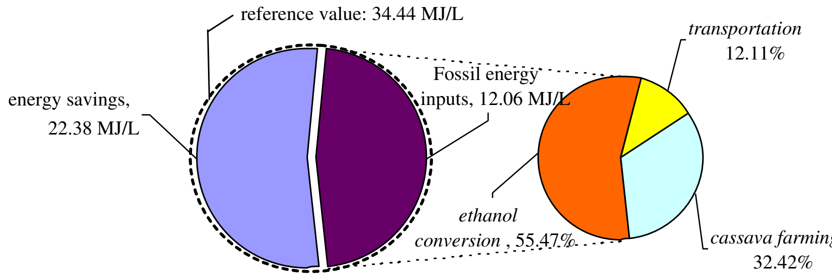

Fig. 2. Net energy balance and fossil energy inputs by segments.

Table 2
Segregation of fossil fuel inputs in cassava ethanol system

Fossil fuels	Amount (MJ/L ethanol)	%
Coal	0.35	2.88
Natural gas	1.65	13.69
Diesel	2.91	24.12
Fuel Oil	7.15	59.31
Total	12.06	100

Table 3
Energy performance comparison between ethanol from cassava in Thailand and ethanol from other feedstocks

Feedstock/ country	Net fossil inputs[a] (MJ/L)	$SR_{EtOH-CG}$	Ref. value (MJ/L)	EnB (MJ/L)
Sugar beet and wheat in Germany	14–35	0.65[b]	23.3	−11.7–9.3
Cassava in China	13.30	0.71[c]	28.44	15.14
Corn in the US	12.76	1.00[d]	40.2	27.44
Cassava in Thailand	12.06	0.89	34.44	*22.38*
Herbaceous biomass in the US	2.01	1.00[d]	40.2	38.2
Sugar cane in Brazil	0.96	1.00[e]	42.3	41.34

[a]Net fossil inputs = gross fossil inputs−co-product energy credits.
[b]Based on fuel energy content (Henke et al., 2005).
[c]Based on fuel economy Feg (L/100 km): Feg CG car = 7.0 (Hu et al., 2004b), Feg E10 car = 6.8 (Lamb, 2006).
[d]Based on GREET's assumption (Wang, 2006): no difference in fuel economy between CG and E10.
[e]1 L of anhydrous ethanol (E-25 engine) produces the same performance as 1 L of CG (Macedo et al., 2004)

production. However, its contribution to the whole system is relatively small, only 9.5% of the total fossil energy inputs.

As far as depletion rates of fossil energy resources are of concern, fossil energy inputs in CE system were segregated by fuel types, e.g., coal, natural gas, diesel and fuel oil. As shown in Table 2, 83.4% of fossil-based energy consumed in CE system is derived from fuel oil and diesel. It shows that in this case study, CE still needs to rely on a large portion of oil-derived liquid fuels, the reserves of which are rapidly being used up whereas for natural gas or coal, the outlook seems brighter.

As mentioned by Henke et al. (2005), the substitution ratio between ethanol and gasoline ($SR_{EtOH-CG}$) derived by studies on ethanol's performance varies in the range 0.65–1.00. It leads to difficulty in an EnB comparison between CE in Thailand and ethanol from other feedstocks in other countries, though simple calculations can be done to get approximate values. For comparison purposes, a closer look at the intensity of net fossil energy inputs for the production of 1 L of ethanol from different feedstocks would be more relevant. All information in this regard is presented in Table 3. Feedstocks selected to be compared with cassava in Thailand (this study) for ethanol production are cassava in China (Dai et al., 2006), corn in the US (Shapouri et al., 2004), wheat and sugar beet in Germany (Henke et al., 2005), herbaceous biomass in the US (Wang, 2006), and sugar cane in Brazil (Macedo et al., 2004).

As a whole, the result is most favorable for sugar cane as a feedstock for ethanol production in Brazil, followed by herbaceous biomass in the US. Energy balances for wheat and sugar beet in Germany were found to be negative in some cases. The production of CE in Thailand consumes about 10% and 5.5% less fossil energy than the production of CE in China and corn ethanol in the US, respectively. It is worth noticing that though the EnB estimate in this study was based on large-scale plant projections from pilot-scale ethanol plant, the results obtained are quite comparable with those of commercial-scale ethanol plants. This serves as an indirect confirmation of the validity of the projections of this study to large-scale production plant.

4.2. GHG balance and GHG abatement cost

4.2.1. GHG balance

As indicated by the results shown in Table 4, CE system in Thailand can provide reduction in GHG emissions compared to CG as a base case; the production and use of one litre of CE can avoid 1.6 kg CO_2 eq. which corresponds to a 62.9% GHG reduction. Taking into account the production target of 3.4 ML of CE per day, a rough estimation can be made that the use of this biofuel would

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reduce GHG emissions by 2 million tonnes CO_2 eq./year or 0.5 million tonnes carbon eq./year.

Table 4 also shows the distribution of GHG emissions by segments. As expected, fossil fuel use contributes much more GHG emissions than soil N_2O emissions plus CH_4 and N_2O emissions from biogas burning, 87.03% versus 12.97%. Consistent with EnB analysis, again, ethanol conversion is the segment having high contribution of GHG emissions (59.12%) due to high consumption of fossil oil. Following ethanol conversion segment are cassava farming/processing and transportation, accounting for GHG emission contribution of 30.15% and 10.73%, respectively. GHG emissions associated with fossil fuel consumed to support human labor account for almost 31.2% of emissions assigned for cassava cultivation/processing. However, its contribution to the whole system is relatively small, only 8.2% of the total GHG emissions.

Table 4
Cassava ethanol life cycle GHG emissions

Items	g CO_2eq.[a]/L EtOH	% contribution
GHG emissions due to the use of fossil fuels	839	87.03
Cassava farming/processing	*253*	*30.15*
Fertilizers and herbicides	90	
Diesel fuel	84	
Labor	79	
Conversion	*496*	*59.12*
Bunker oil	472	
Electricity	24	
Transport (diesel fuel)	*90*	*10.73*
Other GHG emissions	125	12.97
Soil N_2O	*123*	
CH_4 and N_2O emissions from biogas burning	*2*	
Total GHG emissions	964	
Gasoline fuel-cycle GHG emissions (excluding CH_4 and N_2O emissions from use phase)	2,918	
Gross avoided emissions	$-2{,}918 \times 0.89 = -2{,}597$	
Net avoided emissions	$-2{,}597 + 964 = -1{,}633$	
% reduction	62.9	

[a]The GWP (time span of 100 years) of CO_2, CH_4 and N_2O is 1, 23 and 296, respectively (IPCC, 2001).

According to IEA (2004), the use of ethanol from grains, mainly corn and wheat, can provide a 20–47% reduction in well-to-wheels GHG emissions compared to CG. Ethanol from sugar beet is even better at a 56% GHG reduction. Notable cases are sugar cane ethanol in Brazil and cellulosic ethanol in all regions with GHG reduction rates falling in the range of 70–90% or higher. Table 5 summarizes life cycle GHG impacts of ethanol from cassava in Thailand in comparison with ethanol from other feedstocks, e.g., corn in the US (Wang, 2006), herbaceous biomass in the US (Wang, 2006), cassava in China (Hu et al., 2004a) and sugar cane in Brazil (Macedo et al., 2004). Consistent with the energy balance result, CE in Thailand can provide a relatively high GHG emission reduction benefit, which ranks third after cane ethanol in Brazil and herbaceous ethanol in the US as can be seen in Table 5.

4.2.2. *Cost of ethanol produced from cassava in Thailand*

The cost breakdown for CE production was adapted from the 2003 cost estimate prepared by the research team in CSTRU, Bangkok, Thailand (Ronjnaridpiched et al., 2003). The estimate was first made for commercial plant with a production capacity of 100,000 L/d in the 2003 record and then 200,000 L/d in the 2006 update. The production cost of ethanol (termed ex-distillery price) is an aggregation of various cost/value items as listed in Table 6. The feedstock cost of ethanol conversion is the cost of cassava chips on the open market. About 2.5 tonnes of fresh cassava roots are needed to make 1 tonne of cassava chips. Historically, the price of cassava roots has changed from Bt930 in 2003 to Bt1500 a tonne at present, making the price of cassava chips vary from Bt2500 to Bt4000 a tonne. New feedstock cost brings ethanol ex-distillery and ex-refinery price to Bt22.06 and Bt22.45 a litre, respectively (Table 6). For comparison with ULG 95, ethanol ex-refinery price is converted to baht per gasoline-equivalent litre.

Table 6 also shows that feedstock is the dominant contributor to CE production cost. Studies conducted earlier also arrived at a similar conclusion about the cost structure of biofuels (Balagopalan et al., 1988; IEA, 2004). Thus, a preliminary comparison of feedstock cost per litre of ethanol could be roughly used to weigh the feasibility of raw materials for ethanol production. Such comparison

Table 5
GHG emission comparison between ethanol from cassava in Thailand and ethanol from other feedstocks

Feedstock	Gross emissions less emissions displaced by co-products (g CO_2eq/L EtOH)	$SR_{EtOH-CG}$	Avoided emissions (g CO_2eq/L EtOH)		% reduction
			Gross	Net	
Cassava in China[a]	1538	0.71	2006	−468	23.3
Corn in the US	1506	1.00	2920	−1414	48.4
Cassava in Thailand	964	0.89	2597	−1633	62.9
Sugar cane in Brazil	256	1.00	2820	−2564	90.9
Herbaceous biomass in the US	245	1.00	2920	−2675	91.6

[a]GHG emissions include only CO_2 emissions

Table 6
Detailed cost of ethanol production from cassava chips

Items	THB (Thai Baht)/litre	% contribution
Feedstock (cassava chips)	12.01	65.34
Ethanol conversion	6.37	34.66
Chemicals	1.43	
Utilities (bunker oil, electricity)	2.42	
Repair and maintenance	0.21	
Insurance	0.14	
Wage and salary	1.34	
Depreciation	0.83	
Total production cost (ex-distillery price)	18.38	
Profit margin	3.68	
Ex-distillery price	22.06	
Ethanol transportation/distribution	0.39	
Ex-refinery price	22.45	
Ex-refinery price per gasoline-equivalent litre	25.22	

Table 7
Comparison of current feedstock cost per litre of ethanol produced

	THB/tonne	L ethanol/tonne	Feedstock cost (THB/L ethanol)
Cassava chip	3900–4000[a]	333[d]	11.71–12.01
Sugar cane	1100–1200[b]	70[e]	15.71–17.14
Molasses	5270[c]	260[e]	20.27

[a]AFET (2006).
[b]Prasertsri (2006)—USDA Foreign Agricultural Service.
[c]Nation Internet (2006).
[d]Estimated from Ronjnaridpiched et al. (2003).
[e]DEDE (2004c).

made for ethanol production in Thailand concerned with the three potential feedstock types (Table 7) partly shows that ethanol produced from cassava should be cheaper than from molasses or sugar cane.

4.2.3. GHG abatement cost

The event of escalating oil prices recently has narrowed the gap in price between ethanol and CG. In Thailand, ex-refinery price per gasoline-equivalent litre of CE is 6.24 THB higher than the refinery gate price of ULG 95. Taking into account net avoided emissions per litre (1633×10^{-6} t CO_2 eq.) and incremental cost per litre (Bt6.24 or US$0.161, given the average exchange rate for the first seven months of 2006: 1USD = 38.72 THB), one can calculate the GHG abatement cost of CE in Thailand as US$99 per tonne of CO_2-equivalent. It is about 1.4 times the reference cost, US$69.6/t CO_2 eq., at which ethanol would be a reasonable option for climate change mitigation.

In fact, even US$69.6 is not a first-best option for climate policy in Thailand; there are other GHG mitigation options which are more attractive at the costs ranging from US$43.4 to US$-323.1/t CO_2 eq. Fig. 3 shows the potentials of improvement in GHG abatement cost

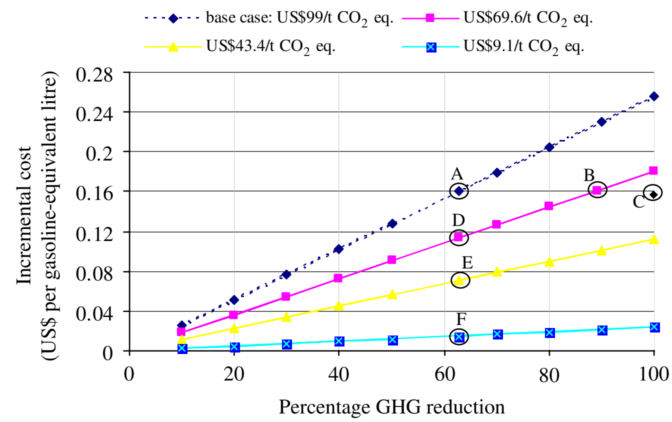

Fig. 3. Potentials of improvement in GHG abatement cost of cassava ethanol in Thailand.

expected for CE in Thailand. The incremental cost of CE (US$ per gasoline-equivalent litre) over CG is plotted against a range of percentage GHG reduction. The first line from the top in the figure is a series of different combinations of incremental cost and GHG reduction resulting in an abatement cost of US$99/t CO_2 eq., which corresponds to CE case study in Thailand (point A in Fig. 3). The lower lines (US$69.6, US$43.4, and US$9.1/t CO_2eq.) represent the most likely cases in which ethanol strategy would be attractive to policy makers as it approaches the three options appearing at the bottom of the list of least cost GHG mitigation strategies for Thailand.

Hypothetically, Fig. 3 shows that if CE could cut GHG emissions by 89.2%, the abatement cost would approach US$69.6/t CO_2 eq., even if the incremental cost remains unchanged (point B in Fig. 3). Point C in the figure indicates that if CE can provide very high rate in GHG reduction, say 100%, the abatement cost would drop to US$62/t CO_2 eq.

Since GHG abatement cost depends not only on GHG reduction but also on the incremental cost of CE (per gasoline-equivalent litre), either a decrease in ethanol production cost or an increase in gasoline price would favor ethanol's strategy for climate policy. A drop in incremental cost of ethanol to $US0.114 or Bt4.40 would be as efficient as a GHG reduction of 89.2% to bring abatement cost close to $US69.6/t CO_2 eq. (point D). Further decreases in the incremental cost of ethanol over gasoline to $US0.071 and $US0.015, or Bt2.74 and Bt0.58 per litre respectively, make ethanol a better option for climate policy with GHG abatement costs corresponding to points E and F on the two bottom lines in Fig. 3.

In fact, rising oil prices would make the production cost of ethanol increase accordingly, since ethanol is still a product of an oil-based economy (83.4% of energy consumption in ethanol production is derived from oil). The gap could effectively get narrower with a decrease in the costs expended in producing ethanol. It is the case of a

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modest rate of fossil energy inputs in the CE production cycle brought about by appropriate farming practices and advanced ethanol conversion technologies. Cogeneration of electricity and steam is another option for modern ethanol plants to cut down energy costs. In addition, utilization of ethanol by-products would help offset ethanol production cost and avoid GHG emissions from other sectors producing the compatible products that are assumed to be displaced. For instance, biogas is a by-product of ethanol production being used as an energy supply, helping reduce production cost and avoid GHG emissions associated with bunker oil use. In this CE system, biogas recovery can reduce a cost of up to Bt1.25 and avoid 256 g CO_2 eq. per litre of ethanol produced. Without this energy supply, GHG abatement cost would be as high as US$144/t CO_2 eq. Other potential by-products are cassava residues which can be used as process fuel substituting for fossil oil in ethanol conversion. One tonne of fresh cassava can produce about 400 kg of peelings and slurry (NEPO, 2000). High moisture content (67–83%) of these waste materials implies extra drying cost before use and overall efficiency loss. As limited information is available on such a scheme, more research is in need to assess whether it is technically and economically feasible.

5. Conclusions

The results of the study show the positive impacts of using CE on fossil energy use and GHG emissions. The energy balance for the production of ethanol from cassava has been found to be positive, i.e., less amount of fossil fuel is consumed to produce ethanol than the gasoline being replaced. Consistent with a positive energy balance, well-to-wheel GHG emissions of CE in Thailand are relatively low, about 0.96 kg per litre of CE used versus 2.6 kg CO_2 eq. for CG that is substituted.

GHG abatement cost found for CE in Thailand of US$99/t CO_2 eq. exceeds the many other climate change mitigation strategies, which are classified as least-cost options for Thailand. In the short term, the less favorable cost effectiveness of most biofuels has mainly resulted from the excess fossil fuel costs expended in the many processing steps required to upgrade biomass to a high-quality transport fuel. In the long run, trends of cost reduction as well as GHG emission reduction going on with ethanol production development would bring the cost per tonne of CO_2 avoided to lower values. With Thailand, ethanol industry is still young compared to Brazil, the largest ethanol producer in the world. Brazil has over 30 years experience with ethanol, having gone through step-by-step and well-planned expansion program. As of January 2006, it was reported that Brazil could produce ethanol with a price of about US$0.26 a litre, lower than the international price of gasoline of US$0.4 a litre. Despite a lower volumetric energy density compared to gasoline, in Brazil, ethanol is still cheaper per kilometer driven (Luhnow and Samor, 2006). Not only effective in cost, sugar cane ethanol in Brazil also provides very high GHG reduction, about 91% as estimated by Macedo et al. (2004). Its GHG abatement cost must be a negative value most expected to be more attractive by the moment. Much can be learned from the Brazilian fuel ethanol program, of which, its excellent use of energy salvaged from bagasse to power ethanol plant and other industrial sectors, is remarkable.

It is noteworthy to emphasize that many benefits of biofuels cannot be captured adequately through a conventional cost analysis. Briefly, they are (1) Reducing oil imports and saving foreign exchanges, (2) Strengthening self-reliance through reducing foreign debt and debt servicing burdens, (3) Reducing GHG emissions and certain air pollutant emissions, (4) Enhancing technological development, (5) Stimulating domestic agricultural production and expanding the markets for domestic agricultural commodities, (6) Generating rural employment and improving farmers' income (Goldemberg et al., 1988). If these benefits are taken into account in a GHG abatement cost analysis, the cost would be more favorable for CE.

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