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CASE STUDY

Life cycle assessment of fuel ethanol from cane molasses in Thailand

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Abstract
Background, aim and scope After China and India, Thailand is considered another emerging market for fuel ethanol in Asia. At present, ethanol in the country is mainly a fermentation/distillery product of cane molasses, although cassava and cane juice are considered other potential raw materials for the fuel. This study aims to evaluate the environmental impacts of substituting conventional gasoline (CG) with molasses-based gasohol in Thailand.
Materials and methods The life cycle assessment (LCA) procedure carried out follows three interrelated phases: inventory analysis, characterization and interpretation. The functional unit for the comparison is 1 l gasoline equivalent consumed by a new passenger car to travel a specific distance.
Results The results of the study show that molasses-based ethanol (MoE) in the form of 10% blend with gasoline (E10), along its whole life cycle, consumes less fossil energy (5.3%), less petroleum (8.1%) and provides a similar impact on acidification compared to CG. The fuel, however, has inferior performance in other categories (e.g. global warming potential, nutrient enrichment and photochemical ozone creation potential) indicated by increased impacts over CG.
Discussion In most cases, higher impacts from the upstream of molasses-based ethanol tend to govern its net life cycle impacts relative to CG. This makes the fuel blend less environmentally friendly than CG for the specific conditions considered. However, as discussed later, this situation can be improved by appropriate changes in energy carriers.
Conclusions The LCA procedure helps identify the key areas in the MoE production cycle where changes are required to improve environmental performance. Specifically, they are: (1) use of coal as energy source for ethanol conversion, (2) discharge of distillery spent wash into an anaerobic pond, and (3) open burning of cane trash in sugar cane production.
Recommendations and perspectives Measures to improve the overall life cycle energy and environmental impacts of MoE are: (1) substituting biomass for fossil fuels in ethanol conversion, (2) capturing CH_4 from distillery spent wash and using it as an energy supply, and (3) utilizing cane trash for energy instead of open burning in fields.

Keywords Cane molasses · Case study · Energy · Environmental performance · Fuel ethanol · LCA · Life cycle assessment · MoE · Molasses-based ethanol · Thailand

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1 Introduction

The production and use of biofuels nowadays has emerged as a critical issue in response to world oil shortages and environmental concerns. Though there are many published papers on bio-ethanol, they are mainly on ethanol from grains, e.g. corn, wheat in the temperate regions (Wang et al. 1999; Shapouri et al. 2004; Kim and Dale 2002; Natural Resources Canada 2003). Molasses, a byproduct of the sugar industry with up to 50% fermentables, is considered a common feedstock for the alcohol industry in tropical countries. In Thailand, three types of raw materials regarded as having high potentials for ethanol production are cassava, molasses and sugar cane. The Thai government has a policy to encourage fuel ethanol production from molasses, taking advantage of the available supply, simple conversion process as well as existing sugar-based distillery infrastructure. As shown in Fig. 1, molasses ethanol production cycle includes sugar cane production, sugar/molasses production and ethanol conversion. Also presented in the figure is relevant information about the mass flow in the system on the basis of 1 tonne cane stalks at harvest.

The objective of this study is to perform a life cycle energy and environmental performance analysis of molasses-based ethanol as a 10% blend with gasoline as a transportation fuel in Thailand. The following parameters have been considered:

- Energy use [megajoule (MJ) energy carrier)], specified as: (1) net energy use (total fossil and non-fossil energy use, excluding energy recovered from system co-products), (2) fossil energy use and (3) petroleum use
- Environmental impact potentials in four categories: (1) global warming potential (GWP); (2) acidification potential (AP); (3) nutrient enrichment potential (NP); and (4) photochemical ozone creation potential (POCP)
- Land use

2 Life cycle assessment

2.1 Molasses-based ethanol fuel case study and functional unit

Sugar cane, the essential raw material for sugar industry in Thailand, is found abundantly in the central region accounting for the highest percentage of the national sugar cane production (OAE 2004). Relevant information on sugar/molasses production and ethanol conversion was obtained from a typical sugar mill and ethanol distillery in Thailand, respectively.

In this study, the functional unit (FU) chosen to compare E10 and conventional gasoline (CG) is 1 L gasoline equivalent consumed by a new passenger car to travel a specific distance. PTT Research and Technology Institute, Thailand has conducted tests for cars running on gasoline and gasohol E10 (Tantithumpoosit 2004). The test results based on Toyota 1.6 L/2000 were used in this study. The car running on E10 gets fewer kilometres per litre than on CG: 13.31 versus 13.46 (PTT 2006). Fuel economy comparison reveals that 1 L of E10 is equal to 0.989 L of CG. The relative performance of new vehicles, which has been acknowledged in various other studies (Brekke 2005; Fu et al. 2003; Macedo et al. 2004), is that 1 L of low ethanol blends is equal to 1 L of gasoline. This analysis, therefore, presents a conservative assignation of environmental loads to ethanol in the form of E10.

2.2 Allocation procedure for molasses use in ethanol production and scenarios

To estimate energy use and emissions associated with molasses input in ethanol conversion, an allocation between molasses and sugar based on their contributions to the economy was set up. The year 2006 marked a significantly increased use of molasses for ethanol production in Thailand compared to 2005 (Preechajarn et al. 2007). In the Thai product market, average prices over the year 2006 for molasses and sugar were THB4,000 (US$105) and THB14,980 (US$394) a tonne, respectively (Prasertsri

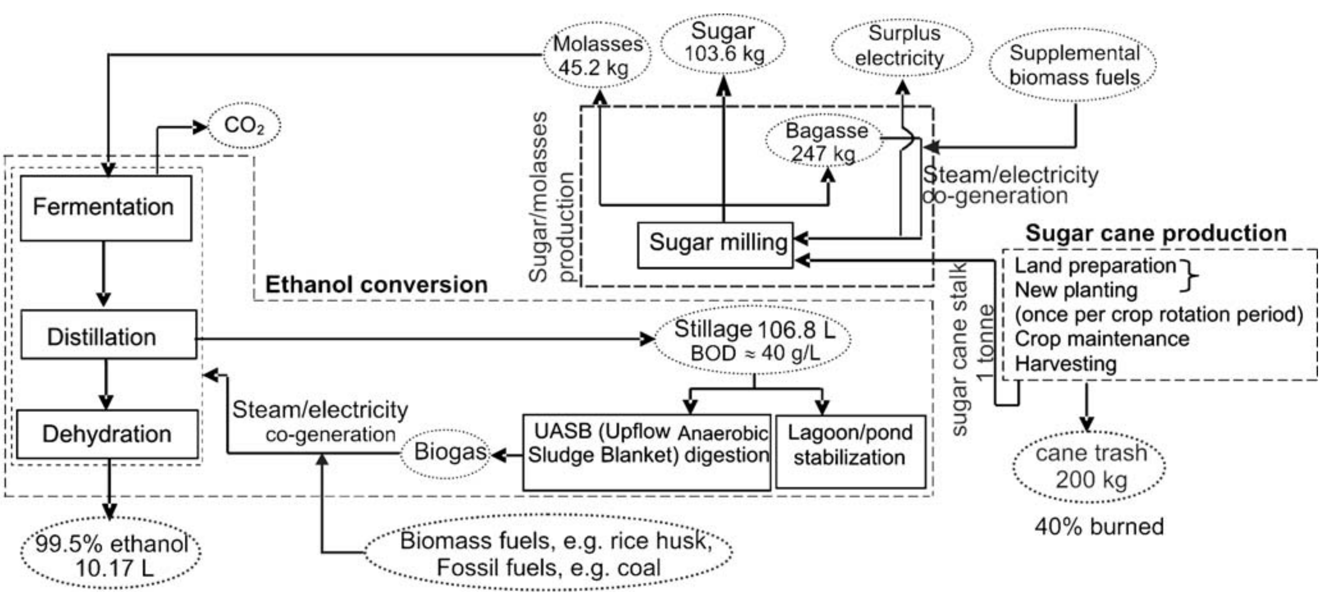

Fig. 1 Flow chart of molasses-based ethanol production process in Thailand

Table 1 Scenarios of molasses-based ethanol case study

Case	Process energy source	% cane trash burning in fields
Scenario 1: E10-a, MoE-a (base case)	Coal, rice husk and biogas recovered from 12% spent wash (the remaining 88% sent to an anaerobic pond)	40
Scenario 2: E10-b, MoE-b	Rice husk and biogas recovered from 100% spent wash	40
Scenario 3: E10-c, MoE-c	Cane trash and biogas recovered from 100% spent wash	0
Scenario 4: E10-a(nb)	Same as E10-a but cane trash burning outside system boundary	0
Scenario 5: E10-ahl	Same as E10-a but including human labour in farming stage	40

2006). About 103.6 kg of sugar and 45.2 kg of molasses are extracted from 1 tonne of sugar cane (Prasertsri 2006). Thus, the relative contribution of sugar and molasses to the economy has the ratio of 8.6:1. Based on this ratio, energy use and emissions from sugar cane and sugar/molasses production (including transportation) are allocated between sugar and molasses at 89.6% and 10.4%, respectively. The ratio is substantially lower than the 15.0:1 for 2005 derived by the same allocation method. Escalating molasses price is the main reason for the large variation in allocation ratio. A sensitivity analysis has been conducted to see how the results of the study are affected by changing the allocation ratio.

To enhance crop-based ethanol performance, it is important to consider opportunities to utilize system co-products. With the molasses ethanol system, the three types of utilizable residues are cane trash in sugar cane production, bagasse in sugar production and stillage in ethanol conversion.

In sugar cane production, burning cane trash prior to or after harvesting is commonly practiced to favour manual harvesting and land preparation for new growth. World-wide, there is increased interest in utilizing cane trash as a fuel instead of open burning in fields. Research has shown that up to 50% trash can be removed without leaving behind any negative effect on soil quality (Gabra 1995). However, such a utilization scheme needs to take into account energy and environmental costs associated with collecting, hauling and preparing trash for off-season use.

In sugar production, bagasse is being utilized as the major fuel to generate both process steam and electricity. The surplus electricity sold to the grid is counted for both energy and environmental credits.

The distillation residue from the production of ethanol, called stillage or spent wash, can be refined into biogas via advanced anaerobic digestion systems, e.g. UASB reactors (Fig. 1). This has been considered a good measure to secure

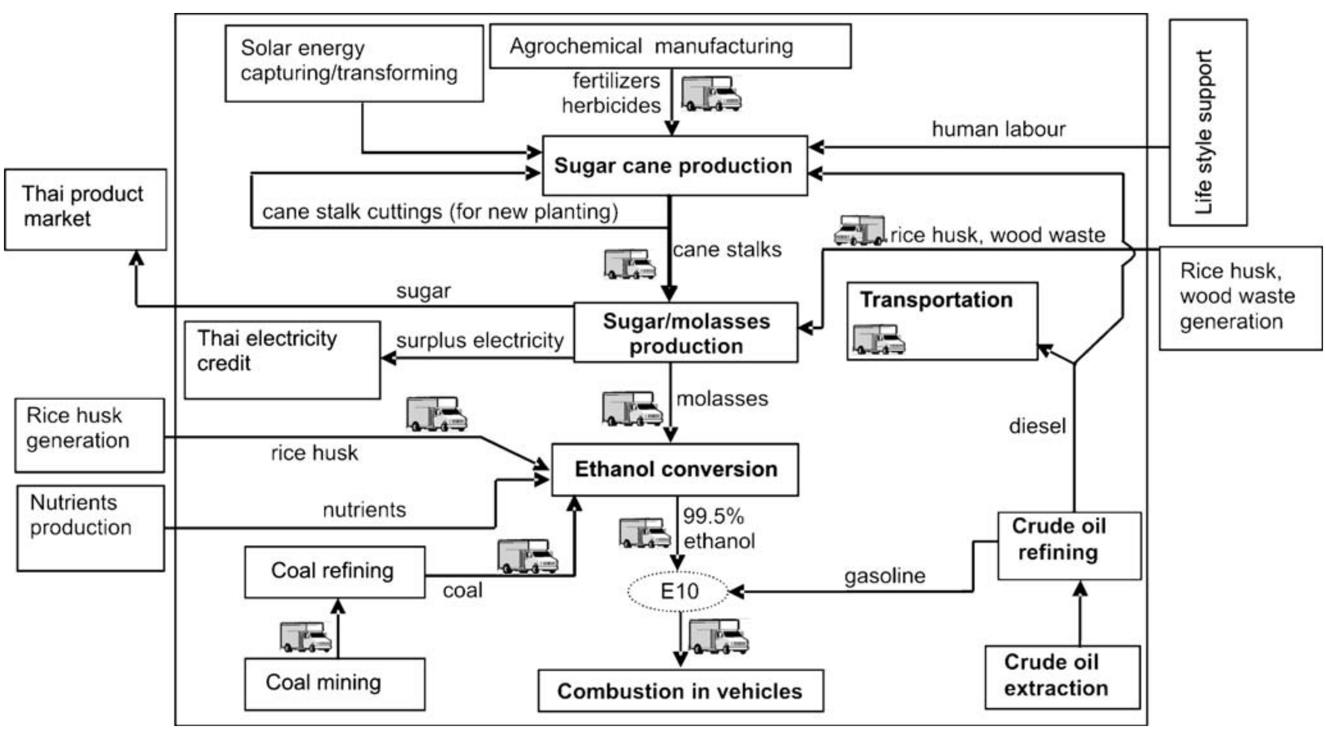

Fig. 2 System boundary of molasses-based ethanol E10 fuel life cycle (base case)

energy and avoid CH_4 emissions to the atmosphere from open anaerobic pond/lagoon system (Nguyen et al. 2007).

Ethanol is more environmentally friendly if less fossil fuel is consumed to produce it. Since sugar cane production is one unit process in molasses ethanol production cycle, cane trash burning essentially plays a role in the environmental performance of the fuel. Accordingly, four main scenarios concerned with process energy sources in ethanol conversion and cane trash burning have been examined (Table 1). The first scenario [E10-a, molasses-based ethanol (MoE)-a] represents the base case in which the process energy sources in ethanol conversion are coal, rice husk and biogas recovered from 12% spent wash and the fraction of cane burned is 40% [this has been verified with the national record (Prammanee 2005)]. The second (E10-b, MoE-b) uses the same assumption as the first in 'cane trash burning' condition but assumes that the plant's energy demand is met by using biogas recovered from 100% spent wash and rice husk as a supplemental fuel. The third one (E10-c, MoE-c) substitutes cane trash collected from cane fields after unburned harvesting for rice husk in the second scenario. The fourth E10-a(nb), in fact, is a sub-scenario of E10-a, simply putting cane trash burning outside the system boundary.

It is of consideration to examine how efficient a crop-based fuel system is in terms of energy production, i.e. whether more energy is produced than is consumed. Such analyses require inclusion of all energy inputs, including human labour. The estimation procedure for the energy value of Thai farm workers and environmental impacts associated with that amount of energy consumed to support labour is given in Nguyen and Gheewala (2008). In the context of lacking a generally acceptable accounting method, this study provides the results without human labour but includes a sensitivity analysis to see how the

Table 2 The procedure for life cycle inventory of molasses-based E10 fuel

Main unit process	Data required	Data source	Collecting method	Data processing
Sugar cane production	– Fuel use – Fertilizer use – Herbicide use – Labour use – Cane trash burning	Sugar cane farmers Thai research reports (Prammanee 2005, Ando 2002, Matsuo et al. 2002, Srijantr et al. 2002, Methacanon 2006)	– Questionnaire – Interview – Literature review	**Energy use** – Diesel: TEI 2001, IFAS 1991 – Fertilizer, herbicide: Helsel 1992; Wang 2006 – Labour: Nguyen and Gheewala 2008 – Electricity: DEDE 2004 – Rice husk: Chungsangunsit et al. 2005 – Biogas: Prakash et al. 1998 – Coal: American Embassy Jakarta 2000; Shapouri et al. 2004 **Emissions** – Diesel, coal, natural gas: Wang 2006 – Fertilizer, herbicide manuf.: Wang 2006 – Fertilizer application (N_2O emissions): IPCC 1997; IPCC 2000 – Labour: Nguyen and Gheewala 2008 – Electricity: Lohsomboon and Jirajariyavech 2003; Wang 2006 – Biomass/biogas combustion in boilers: Wang 2006; DMU/NERI 2006 **Fuel substitution ratio derivation** – Boiler efficiency: CIBO 2003; Omori 2006
	Cane trash utilization	Philippines case study (Samson et al. 2001)		
Sugar/Molasses production	– Production capacity – Fuel use – Surplus electricity sold to the grid	Sugar factory	– Questionnaire – Interview	
Ethanol conversion	– Fuel use – Production capacity – Spent wash treatment/ utilization	Ethanol factory		
All transportation activities involved in the system	Transport – mode – capacity – distance	– Rayong Bulk Terminal Company Limited – Sugar cane farmers – Sugar factory – Ethanol factory	– Questionnaire – Interview	
– Crude oil recovery – Gasoline refining	Fuel energy content	Thai research report (TEI 2001)	Literature review	**Energy use**: TEI 2001; IFAS 1991; Wang 2006 **Emissions**: Wang 2006
Fuel combustion (Use stage) – CG, E10	– Fuel energy content – Fuel economy	– Thai research report (TEI 2001) – USDA research report (Shapouri et al. 2004) – PTT (PTT 2006)	Literature review	**Energy use** – Gasoline: TEI 2001 – E10 – CG portion: TEI 2001; ethanol portion: using – heating value of ethanol (non-fossil energy) **Major emissions**: PTT 2006

results would change if labour is included. The fifth scenario E10-ahl is thus nothing but scenario E10-a including human labour.

2.3 System boundary and data sources

As shown in Fig. 2, the main unit processes of the molasses-based E10 fuel system for the life cycle inventory (LCI) are sugar cane production, molasses production, ethanol conversion, oil extraction and refining, transportation and fuel combustion in vehicles. The system boundary also includes various sub-processes associated with the five main processes, viz. agrochemical manufacturing, and coal mining/cleaning. Energy stored in biomass (sugar cane crop) is counted as the non-fossil energy consumed when the bio-ethanol is burned in vehicles (i.e. use stage). Environmental loads associated with the manufacturing of nutrient input in ethanol conversion are considered negligible compared to other inputs and thus are not included in the analysis. Also excluded from the system is the generation of waste products from rice milling and timber processing, viz. rice husk and wood waste.

The procedure for LCI of the molasses-based E10 fuel is summarized in Table 2. The fuel life cycle consists of two main stages: upstream stages (feedstock production, fuel conversion) and use stage (fuel combustion in vehicles). With E10, feedstock stage includes sugar cane/molasses production and crude oil recovery, and fuel stage is a combination of ethanol conversion and CG refining. As seen, data for the study were collected in different ways from different sources. An important step of the LCI procedure is processing data obtained to quantify energy use and emissions associated with each unit process using well-known models, conceptual guidelines and databases (see Table 2). Notably, emission factors for different combustion systems fed by different fuels were estimated mainly from GREET (Wang 2006). GREET derives these emission factors based on the fifth edition of EPA's AP-42 document considering control technologies that were in place in the early 1990s when the 1990 Clean Air Act Amendment was brought into effect. In terms of vehicle emission control technology, catalytic converters have been installed on gasoline cars in Thailand since 1993 (ADB 2006). Key assumptions for emissions from cane trash open burning and anaerobic pond treating stillage are presented separately in Table 3.

A rough assessment of the potential of cane trash as a supplemental energy source in addition to biogas captured from stillage is summarized in Table 4. As seen from the table, the energy available from cane trash produced per tonne cane is about 1,550 MJ. Multiplying by the allocation ratio for molasses gives the amount of energy secured from cane trash that would be available for MoE. It is in excess of the energy required to fill the gap between MoE energy requirement and the energy recovered from biogas: 161 versus 138 MJ. The surplus cane trash is assumed to be utilized for electricity production. After accounting for electricity generation loss, an approximate amount of 1.4 kWh would be exported to the grid, for which both energy and environmental credits are considered.

3 Results and discussion

3.1 Life cycle energy and environmental performance

Table 5 presents the life cycle assessment (LCA) characterization results for E10-a and CG. Change represents impacts of substituting the fuel alternative for CG. Negative change implies a reduction in environmental loads compared to gasoline, whilst positive change denotes an increase. The results excluding cane trash burning are also given in columns E10-a(nb) for a comparison with E10-a. Breakdown of E10-a and gasoline life cycle energy and

Table 3 Default parameters for estimating emissions from cane trash open burning and anaerobic pond stabilization

Pollutant	Anaerobic pond stabilization		Cane trash open burning			
	kg/kg BOD	Estimating procedure/ Conceptual guideline/ Methodology	C fraction of trash = *A* (ONEP 1990)	Emission ratio (ONEP 1990)	N/C (ONEP 1990)	Emission (g/kg dry matter)
CH_4	0.22	Nguyen et al. 2007; AGO 2003; IPCC 2000	0.5268	5 g C/kg C in trash		$A \times 5 \times 16/12 = 3.5$
CO			0.5268	60 g C/kg C in trash		$A \times 60 \times 28/12 = 73.8$
N_2O			0.5268	7 g N/kg N in trash	0.012	$A \times 0.012 \times 7 \times 22/14 = 0.07$
NO_x			0.5268	121 g N/kg N in trash	0.012	$A \times 0.012 \times 121 \times 46/14 = 2.5$
NMVOC						2-6 (US EPA 1995)
SO_2			S% 0.1 (IEA 2007)	Assumption: 60% S converted to SO_2 (Reddy and Venkattaraman 2002)		$1 \times 0.6 \times 64/32 = 1.2$

Table 4 Potential of cane trash as a supplemental energy source in addition to biogas captured from distillery spent wash per tonne cane

Energy from cane trash allocated to molasses (MJ)	MoE (L)	Stillage (L)	Energy required in MoE conversion (MJ)	Energy recovered from biogas (MJ)	Energy required from trash (MJ)
15.5[a]×200[b]×0.5×0.104=161.2	10.17[c]	10.17×10.5[d]=106.8	19.93[e]×10.17=202.7	0.107×26[f]×23[g]=64.0	202.7−64.0=138.7

Assumptions:
[a] Heating value of cane trash=15.5 MJ/kg (EFE 2007)
[b] Cane trash produced=200 kg/t cane (Methacanon 2006)
[c] MoE conversion rate=10.17 l/t cane (on-site data collection from an MoE factory in Thailand)
[d] Molasses-based stillage generation rate=10.5 l/l MoE (on-site data collection from an MoE factory in Thailand)
[e] Energy required to convert molasses to ethanol=19.93 MJ/l (estimated from Nguyen et al. 2007)
[f] Biogas recovery rate=22–30 m^3/m^3 stillage (Gupta 1998)
[g] Heating value of biogas=23 MJ/m^3 (Prakash et al. 1998)

environmental impacts into the three stages (feedstock, fuel and end use) is presented in Fig. 3.

The results show that using MoE in the form of E10 as a gasoline substitute leads to fossil energy and petroleum savings. The savings are mainly due to an avoidance of fossil gasoline consumed when the gasoline–ethanol blend is burned in vehicles. In contrast, using the fuel alternative gives rise to an increase in net energy use relative to CG. Such an increase is contributed primarily by feedstock and fuel stages where higher energy use over CG outweighs lower energy use at the use stage (see Fig. 3). It can be seen that per FU, MoE feedstock and fuel stages consume more energy than CG. As a result, an addition of MoE to CG to make E10 blend raises energy usage intensity of these stages over E0 (CG).

For GWP, POCP and NP, higher impacts from the upstream of E10 govern the net impacts of the fuel life cycle relative to CG. This results in the E10 blend being less environmentally friendly than CG. Considering AP, a higher impact from the upstream of E10 over that of CG is compensated by lower impact from the use stage (see Fig. 3).

Putting cane trash open burning outside the system boundary decreases the environmental loads assigned to the ethanol blend. The magnitude of the decrease is in the order of 0.1% for GWP to 13.1% for POCP. It implies that cane trash burning contributes largely to POCP via CO and volatile organic compound (VOC) emissions.

The sugar industry in Thailand produces approximately 3 million tonnes of molasses a year, 60–70% of which is consumed for liquor and animal feed. The surplus 30−40% is thus feasible to be converted to 0.8 million litres (ML) ethanol a day (Sriroth et al. 2003). As such, there is possibly some change in land use to grow crops to substitute molasses in its current use. Applying the same allocation procedure (see Section 2.2) to allocate land use between molasses and sugar, the figures of land use per tonne molasses and then per litre MoE were identified. This gave a rough evaluation of the area of land use for growing feedstock (sugar cane) to produce the ethanol portion in E10 (see Table 5). The production of 0.8 ML ethanol a day or 240 ML a year from the surplus molasses corresponds to the use of approximately 43,000 ha of land a year.

3.2 Breakdown of results: comparison between scenarios

A breakdown of contributions to the environmental impacts from base case ethanol production cycle is performed in Fig. 4.

Figure 4 indicates that ethanol conversion has noticeable effects on almost all categories considered, e.g. net energy use, fossil energy use, GWP, AP and NP. For all impact

Table 5 LCA characterization results for 8 impact categories (displayed per functional unit)

Impact category	CG	E10-a		E10-a(nb)	
			% change relative to CG		% change relative to gasoline
Net energy use (MJ)	38.70	39.95	+3.2	39.95	+3.2
Fossil energy use (MJ)	38.59	36.55	−5.3	36.55	−5.3
Petroleum use (MJ)	34.83	32.00	−8.1	32.00	−8.1
GWP (kg CO_2 eq.)	2.99	3.07	+2.8	3.07	+2.7
AP (g SO_2 eq.)	3.29	3.29	+0.1	3.16	−3.9
NP (g NO_3^- eq.)	5.00	5.10	+2.1	4.94	−1.2
POCP (g C_2H_4 eq.)	1.53	1.79	+17.0	1.59	+3.9
Land use (m^2.year)	–	0.18			

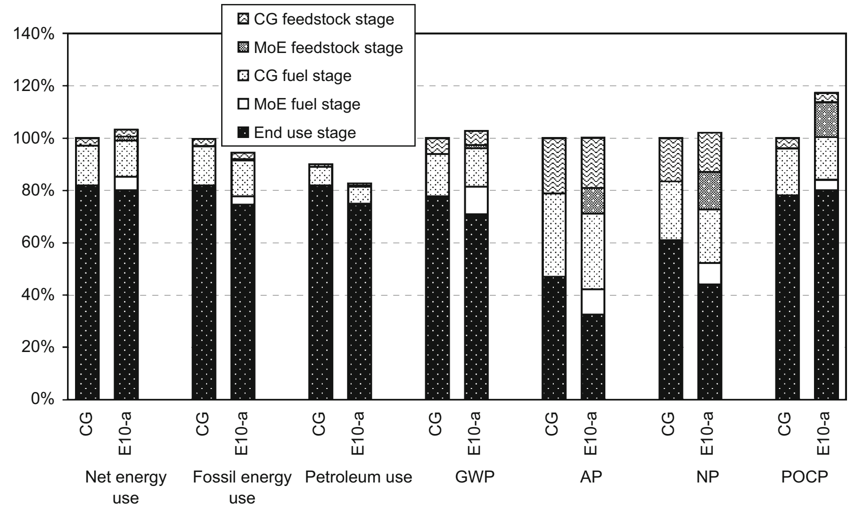

Fig. 3 Contributions of stages (feedstock, fuel, end use) to life cycle energy and environmental performance of CG and E10-a

categories mentioned, the relatively high contribution made by ethanol conversion is due to the use of coal as the main source of plant process energy. CH_4 emissions from anaerobic pond treating stillage contributes largely to GWP, up to 52% of the fuel production cycle greenhouse gas (GHG) impacts. Cane trash open burning in sugar cane production is responsible for emissions of various air pollutants, notably CO and VOC, which contribute substantially to POCP. The contributions from sugar/molasses production to all impact categories are not as significant as those from ethanol conversion or sugar cane production, except NP (33.6% versus 27.5% and 29.6% from sugar cane farming and ethanol conversion, respectively). The energy and environmental credits resulting from the sale of surplus electricity to the grid are displayed in Fig. 4 as separate sub-category percentage for each impact category. Since a major part of the process energy in MoE production cycle is derived from biomass and coal, petroleum use category is contributed mainly by diesel consumed for transportation (69%). In other impact categories, transportation represents a relatively small contribution (less than 15%) compared to other unit processes in the MoE production cycle.

Figure 5 presents the life cycle energy and environmental performance of E10 fuels (E10-a, -b and -c) in

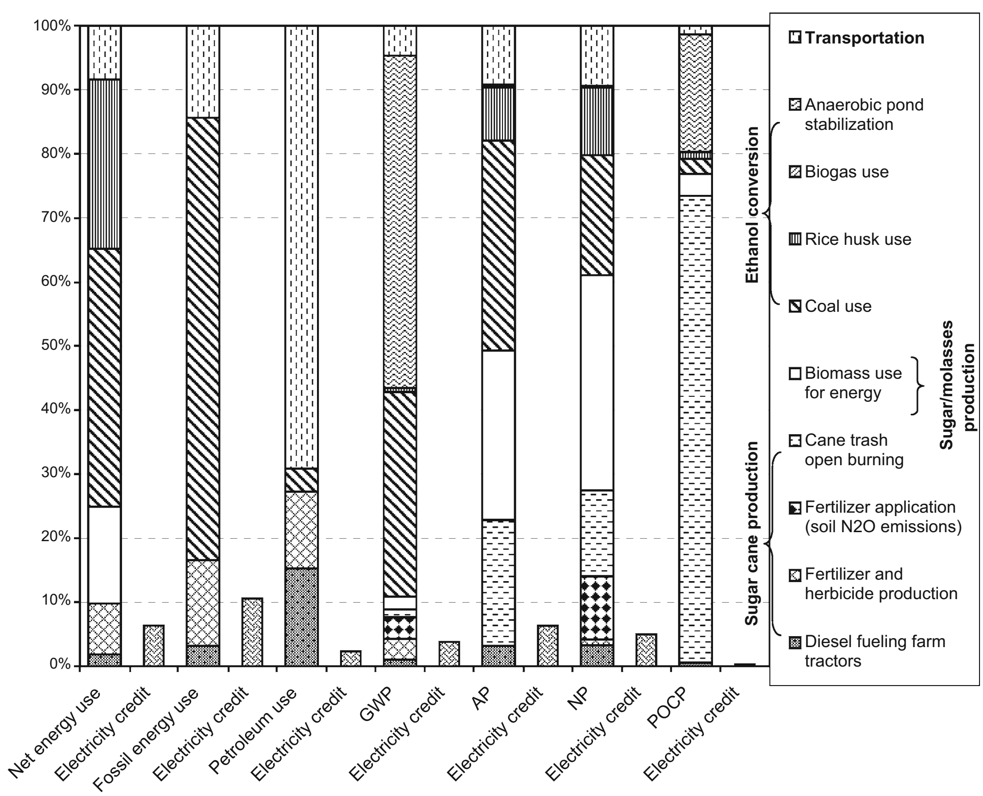

Fig. 4 Characterization results—contributions to the environmental impacts from ethanol production cycle

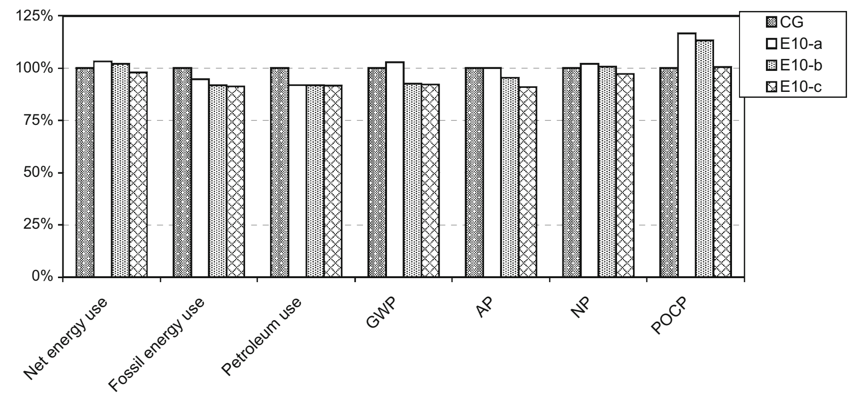

Fig. 5 Comparison of life cycle energy and environmental performance of E10 and gasoline

comparison with CG. As seen from the figure, projection scenario b combining recovery of CH_4 from stillage and substitution of biomass (rice husk) for fossil fuel (coal) holds potentials to improve energy and environmental performance of E10. Notable is GWP for which, under the projection, E10-b becomes more environmentally friendly than CG whilst E10-a is not. Utilization of cane trash for energy instead of open burning yields even more improvements in reducing impacts on AP, NP and, especially, POCP.

To make the results of ethanol not diluted in the 90:10 gasoline–ethanol blend, a comparison between 'a unit of gasoline versus a gasoline-equivalent unit of ethanol' was made as shown in Fig. 6. The comparison is made for the production phase (upstream) of MoE-a, -b and -c and gasoline since most of emission data for neat ethanol combustion (use phase) are not available. The values for CG serve as references and are hence set at 1. The 'gasoline-equivalent unit of ethanol' was derived based on fuel economy of E10 and gasoline cars in Thailand (Nguyen et al. 2007). The figure shows clearly that molasses ethanol under base case (MoE-a) has inferior energy and environmental performance to gasoline. However, the figure also shows that trends of improvement are high if projection scenarios are taken into account. Remarkably, scenario c makes molasses ethanol more environmentally friendly than gasoline in all impact categories except acidification and nutrient enrichment. It remains to be evaluated whether inclusion of use phase and production phase would significantly change any of the relative values. However, it is anticipated that the inclusion of the use phase will make the results more favourable for ethanol, particularly the fossil and petroleum energy use categories and GWP.

3.3 Sensitivity analyses

3.3.1 Effect of changing allocation ratio between sugar and molasses

The results of the sensitivity analysis for the change of allocation ratio between sugar and molasses over the years 2005 and 2006 are shown in Fig. 7. All corresponding results are displayed as percentages relative to CG. As seen, a decrease in allocation ratio decreases environmental loads assigned to MoE feedstock stage of E10-a. The magnitude of the effect is in the order of 0.2% change for petroleum use to 6.1% for NP. However, the net impacts of the blend relative to CG remain almost unchanged with the change of allocation ratio. The relative effect on any inventory

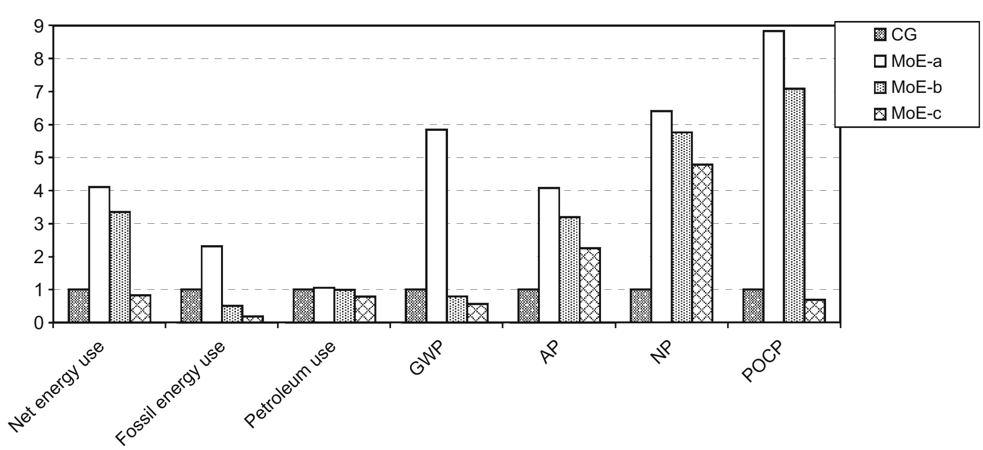

Fig. 6 Comparison between 1 l gasoline and one gasoline-equivalent litre of molasses ethanol (MoE-a, -b and -c), production phase

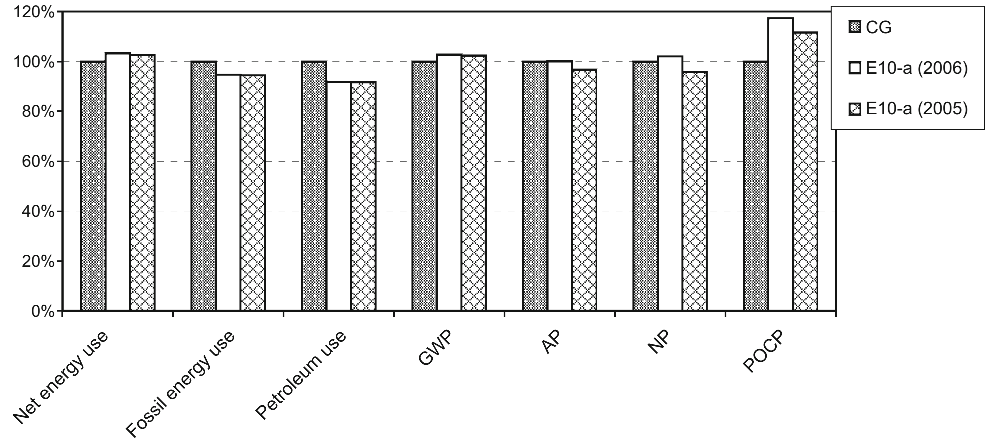

Fig. 7 Effect of allocation ratio change on life cycle energy and environmental performance of E10-a

categories resulting from such a change of allocation ratio corresponds to the relative contribution of MoE feedstock stage to the overall life cycle energy and environmental performance of E10-a (see Fig. 3).

3.3.2 Effect of human labour inclusion

The results of the sensitivity analysis done for the E10 blend with human labour accounting (E10-ahl) versus the base case without human labour (E10-a) are shown in Fig. 8. It can be interpreted that inclusion of human labour in the system does not affect much the results of the study and, most importantly, does not change the overall conclusions regarding the relative advantages or disadvantages of the fuel blend with respect to CG.

3.4 Comparison with cane ethanol production in Brazil: farming stage

A rough comparison between sugar cane production in Thailand and that in Brazil is useful to see where Thailand can improve ethanol energy and environmental performance by looking back at its farming stage. As given in Macedo et al. (2004), total energy expenditures for sugar cane production in Brazil are 13.90 GJ/ha, of which, fertilizers and fuel inputs are the two largest contributors. The figure is about 30% lower than that in Thailand, mainly resulting from a relatively low level of fertilizer energy input. In fact, the amounts of fertilizer applied per hectare by the two countries are almost equal, 195 kg in Brazil (N, 58.3 kg; P_2O_5, 36.7 kg; K_2O, 100 kg) versus 193 kg in Thailand (N, 128 kg; P_2O_5, 37 kg; K_2O, 28 kg), but the main component of fertilizer formulation used in Brazil is K (51.3%), whereas that in Thailand is N (66.3%). As documented, the energy cost of N fertilizer is about nine times that of P (Macedo et al. 2004; Helsel 1992).

The level of GHG emissions from sugar cane production in Thailand is about 23% higher than that in Brazil, 37.8 versus 30.7 kg CO_2eq./t cane. Apart from the difference in the procedure of emission estimation applied by the two case studies, notably for the manufacturing of agrochemicals, lower performance of sugar cane production in Thailand in terms of GHG emissions is most likely accounted for by a relatively high rate of N-fertilizer input. Not only is the manufacturing of N-fertilizer energy intensive, which has implications for a high level of GHG

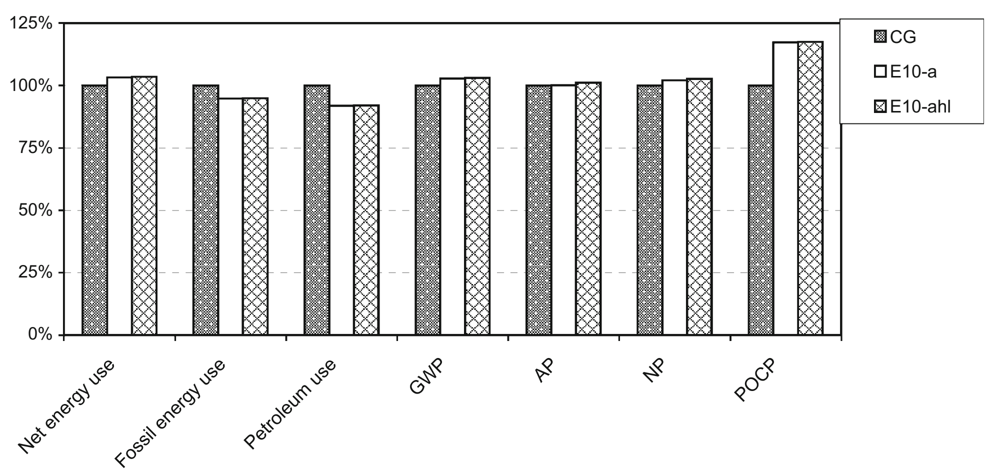

Fig. 8 Effect of human labour inclusion on the overall energy and environmental performance of E10-a

emissions (Macedo et al. 2004; Wang 2006), but the use also gives rise to N_2O soil emissions. There is a need to examine whether a new fertilizer formulation containing less N is appropriate for sugar cane cultivation in Thailand.

4 Conclusions

Based on the results of the study, the main conclusions can be drawn as follows:

- Under the existing production condition, molasses-based ethanol in the form of E10 is competitive to gasoline when fossil energy use and petroleum use are considered.
- Coal used in ethanol conversion is the main source of energy use and environmental impacts. CH_4 emissions from anaerobic pond-treating stillage contributes largely to global warming potential. Capturing this gas and using it for plant energy would bring multiple benefits: saving energy, avoiding environmental impacts of uncontrolled CH_4 emissions and also of CO_2 emissions from coal use. Cane trash open burning in sugar cane farming is a contributor to acidification, nutrient enrichment and, notably, photochemical ozone creation potential.

5 Recommendations and perspectives

Molasses ethanol has a high potential to be improved if the following measures are implemented: (1) turning stillage into green energy via biogas capture and utilization, (2) substituting biomass for fossil fuels in ethanol conversion, and (3) using cane trash for fuel instead of open burning.

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