

Supporting Information (SI)

Long-term bio-ethanol system and its implications on GHG emissions: A case study of Thailand

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S.1 Modelling of the future (long-term) bio-ethanol system in Thailand

According to the targets of producing bio-ethanol in the country as mentioned in the renewable energy development plan (2008-2022), the approved ethanol plants and the ratios of feedstocks used as shown in **Table S1** and complemented with assumptions defined in the main text, the feedstocks supply in future bio-ethanol system would be obtained as seen in **Figure S1**. There was a significant decrease of molasses ethanol production from the first year due to one molasses ethanol plant changing to the production of acetic acid. However, the total ethanol production in 2009 still increased at a low rate due to the slight increase of cassava and sugarcane ethanol production in that year.

Table S1 The approved ethanol plants in Thailand (as of 2 September 2009) (1)

Ethanol plants classified by feedstocks type	Number of plants	Capacity (litre/day)	Feedstocks used
Molasses	5	675,000	Molasses 100%

Molasses/sugarcane	10	2,010,000	Molasses 50%, Sugarcane 50%
Molasses/cassava/sugarcane*	8	1,220,000	Molasses 50%, Cassava 50%
Cassava	24	8,390,000	Cassava 100%
Total	47	12,295,000	

* Only molasses and cassava are used as feedstocks for these 8 molasses/cassava/sugarcane ethanol plants because in fact there is a low possibility for these plants to use all three feedstocks in their production. Therefore, the study assumes that sugarcane can be used as feedstock only in the ethanol plants that operate along with the sugar mills or the ethanol plants designed specifically for using sugarcane as feedstock.

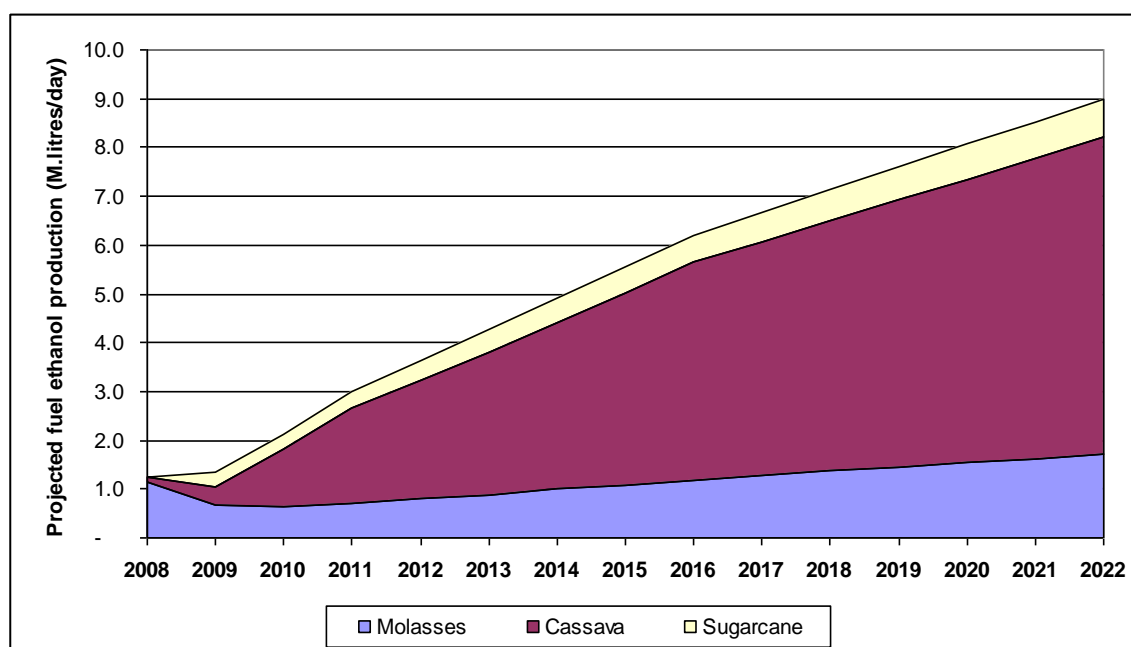


Figure S1 Trends and the projected bio-ethanol production systems in Thailand

S.2 GHG indicators

To evaluate the overall GHG performance of the future bio-ethanol system in Thailand, three GHG indicators used in the assessments are as follows: The average GHG emission factor ($GHG_{EF,ethanol\ avg}$) is an indicator to determine the overall GHG emissions per functional unit of bio-ethanol system which can be determined by equation (1).

$$GHG_{EF,ethanol\ avg} = \sum_i (GHG_{EF,ethanol\ i} \times Fraction_{ethanol\ i}) \quad (eq.1)$$

where i indicates the type of bio-ethanol (e.g. cassava ethanol, molasses ethanol); $GHG_{EF,ethanol\ i}$ is the GHG emission factor of bio-ethanol i ; $Fraction_{ethanol\ i}$ is the proportion of bio-ethanol i contributing to the overall bio-ethanol system in a given year. . This obtained GHG emission factor ($GHG_{EF,ethanol\ avg}$) is further used as the basis to examine the GHG performance of the overall bio-ethanol system by expressing either in terms of the percentage in GHG emissions reduction ($Percent\ GHG_{reduction}$) or the net avoided GHG emissions ($Net\ GHG_{avoided}$). The percentage is just for comparison with the fossil equivalent; but the absolute value gives the actual reduction for the entire system. The basic formats for calculating those two indicators are shown as equation (2) and (3), respectively.

$$Percent\ GHG_{reduction}(\%) = \frac{GHG_{EF,fossil} - GHG_{EF,ethanol\ avg}}{GHG_{EF,fossil}} \times 100 \quad (eq.2)$$

$$Net\ GHG_{avoided}(kg\ CO_2eq) = GHG_{emission,fossil} - GHG_{EF,ethanol\ avg} \times Q_{ethanol} \quad (eq.3)$$

where $GHG_{EF,fossil}$ is the GHG emission factor of fossil fuel system (i.e. gasoline); $GHG_{emission,fossil}$ is the GHG emissions related to the total amount of fossil fuel displaced by the total amount of bio-ethanol ($Q_{ethanol}$) in a given year. The benefit of these indicators is not only to reveal the performance of bio-ethanol system but can also be used by policy makers as one of the basis for granting subsidies to promote the use of biofuels (2).

S.3 Scope of GHG emissions

The life cycle of various bio-ethanol pathways in Thailand is shown in **Figure 1** in the main text. The system is divided into five main stages including land use changes (LUC) for new plantation areas, feedstocks cultivation and harvesting, feedstocks processing, bio-

ethanol conversion and use of bio-ethanol in vehicles. The analyses focus on the three most important GHGs of bioenergy system i.e. carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O) **(3)** and the global warming potential factors used for them are 1, 25, 298 kg CO₂-eq/kg substance, respectively **(4)**. The basic formula to evaluate the total GHG emissions of bio-ethanol is as follows **(5)**:

$$E_{\text{total}} = E_{\text{luc}} + E_{\text{cul}} + E_{\text{fp}} + E_{\text{ecv}} + E_{\text{u}} + E_{\text{td}} + E_{\text{ext}} - E_{\text{cred}}$$

where E_{total} = total GHG emissions from the entire the life cycle of bio-ethanol (kg CO₂ eq/MJ bio-ethanol); E_{luc} = GHG emissions from carbon stock (C-stock) changes caused by land use change and management; E_{cul} = GHG emissions from cultivation and harvesting of feedstocks; E_{fp} = GHG emissions from feedstock processing; E_{ecv} = GHG emissions from bio-ethanol conversion; E_{u} = GHG emissions from the use of bio-ethanol in vehicle; E_{td} = GHG emissions from transport and distribution over the entire life cycle; E_{ext} = GHG emissions from the extraction of input material over the entire life cycle; and E_{cred} = GHG credits obtained from the ethanol production system e.g. credits for biogas recovery, excess electricity from co-generation, etc.

(1) GHG emissions related to land-use change (E_{luc})

Increased further demand for biofuels requires huge amounts of crops supply that might be satisfied by expansion of cultivation land. This can induce both direct and indirect land-use changes (iLUC). Direct land-use change (dLUC) occurs when energy crops for biofuels displace a prior land use (e.g. forest or grassland), while; indirect LUC is the ripple effect that results from using land currently used for other crops for fuel production **(6-8)**. LUCs would possibly result in changes of carbon stocks (e.g. above-and below-ground biomass, soil

organic carbon) elsewhere and bring about substantial amount of GHG emissions. In this analysis, the possible direct LUC caused by increased demand for bio-ethanol in Thailand and its implications on GHG emissions (E_{luc}) are investigated and calculated based on the IPCC guidelines on GHG emissions from LUC (9). The scope of GHG sources includes (1) CO_2 emissions from clearance of land prior to establishment of a new plantation (E_{CL,CO_2}), (2) non- CO_2 emissions i.e. CH_4 and N_2O from biomass burning as part of clearance of historic land prior to establishment of a new plantation ($E_{CL,nonCO_2}$), and (3) emissions from soil carbon stock changes due to land-use change and management ($E_{CO_2, soil}$). Then, the GHG emissions associated with dLUC (E_{luc}) per a hectare of cultivated area [$kg\ CO_2\ eq/(ha.yr)$] can be estimated by distributing its impacts over the life time of land use for feedstock cultivation (T) as follows (5, 9):

$$E_{luc,i} = [E_{CL,CO_2} + E_{CL,nonCO_2} + E_{CO_2, soil}]/T \quad (eq.4)$$

$$E_{CL,CO_2} = [AGB_{historic,i} \times (1 + R_{historic,i})] \times CF_i \times (44/12) \quad (eq.5)$$

$$E_{CL,nonCO_2} = M_{biomass,b} \times C_f \times (EF_{N_2O,b} \times 298 + EF_{CH_4,b} \times 25) \quad (eq.6)$$

$$E_{CO_2, soil} = (SOC_{historic,i} - SOC_{current}) \times (44/12) \quad (eq.7)$$

where i represents type of land prior to be converted to cultivate cassava and sugarcane. Two choices of the transformed lands i.e. tropical dry forest land and grassland converted to cropland are used as scenarios in this analysis for determining the impacts of direct LUC in order to satisfy an increased demand for cassava and sugarcane in the future. These choices are feasible and the same for both crops because the plantation areas of sugarcane and cassava are mainly located in the north-eastern region of Thailand. The annual precipitation of this region is around 1,300 mm/year and average temperature is 27°C which corresponds to "tropical dry" as defined in IPCC's ecological zone. The IPCC's default value of 20 years (9) is used as the time period of land use (T) to estimate GHG emissions caused by LUC for

cassava and sugarcane plantation in Thailand. This is reasonable because Thai farmers generally use the land as long-term plantation even though cassava and sugarcane are harvested annually.

To determine the emissions from soil carbon stock changes by equation (7), the soil organic carbon level in the land (e.g. forestland or grassland) prior to implementation of cassava or sugarcane ($SOC_{historic,i}$) and the soil organic carbon level under the current cassava or sugarcane plantation ($SOC_{current}$) are calculated as follows (5, 9):

$$SOC_{historic,i} \text{ [tC/ha]} = SOC_{Ref} \times F_{LU,historic} \times F_{MG,historic} \times F_{I,historic} \quad (eq.8)$$

$$SOC_{current} \text{ [tC/ha]} = SOC_{Ref} \times F_{LU,current} \times F_{MG,current} \times F_{I,current} \quad (eq.9)$$

The detailed descriptions of parameters used in this LUC analyses are referred from IPCC 2006 and UNFCCC as shown in **Table S2**. Thus, the obtained GHG emissions associated with the conversion of tropical forest land to cropland i.e. E_{CL,CO_2} , $E_{CL,nonCO_2}$, $E_{CO_2, soil}$ are 14.34, 0.15 and 2.09 ton $CO_2eq./ha.yr$, respectively. While, the results of grassland converted to cropland are 0.75, 0.001 and 1.92 ton $CO_2 eq./ha.yr$, respectively.

Table S2 Parameters used in LUC analyses

Parameters		FL	GL
Above-ground biomass (AGB) for FL and GL (t dm ha ⁻¹)	$ABG_{historic,i}$	130.00	2.30
Ratio of BGB/AGB (t root dm t ⁻¹ shoot dm)	$R_{historic,i}$	0.28	0.28
Carbon fraction in dry matter of biomass (t C t ⁻¹ dm)	CF_i	0.47	0.47
Biomass available for burning during first land clearance	$M_{biomass,b}$	10% of AGB	10% of AGB
N ₂ O emission factor for burning of biomass (t N ₂ O t ⁻¹ dm)	$EF_{N_2O,b}$	0.0002	0.0002
CH ₄ emission factor for burning of biomass (t CH ₄ t ⁻¹ dm)	$EF_{CH_4,b}$	0.0068	0.0023
Soil organic C (t C ha ⁻¹)	SOC_{Ref}	31	31
Stock change factor for the historic land-use system	$F_{LU,historic}$	1	1

Stock change factor for the historic land management	$F_{MG,historic}$	1	0.97
Stock change factor for the current land-use system	$F_{LU,current}$	0.58	0.58
Stock change factor for the current land management	$F_{MG,current}$	1.09	1.09
Stock change factor for input of organic matter for the historic situation	$F_{I,historic}$	1	1
Stock change factor for input of organic matter for the historic situation	$F_{I,current}$	1	1

Indirect LUCs are not relevant to this study as the future crop productivity improvement scenarios are applied to model the long-term bio-ethanol system in Thailand. The government's policy goals on cassava and sugarcane yield improvement are 34 and 94 ton/ha by year 2012, respectively (1). However, due to the continual development of genetic technology, there are various high yield varieties of cassava and sugarcane that could reach to 50 and 125 tons/hectare, respectively. This could help increase feedstocks production and avoid the other actions that could possibly result in the indirect LUC effects such the reducing export of cassava and molasses products or expansion of cultivation areas for cassava and sugarcane by converting other croplands. Even though those targeted yields may not help increase feedstock enough to satisfy the increased demand for cassava and sugarcane for food, feed and fuel in the long run as evaluated by Silalertruksa and Gheewala (2010) (10), the deficits are presumably fulfilled by expanding plantation areas. The detailed scenarios used are described in the main text (Section 3.2).

(2) GHG emissions from cultivation and harvesting of feedstocks

Cultivation of energy crops is associated with many inputs such as diesel, fertilizers and agrochemicals that induce GHG emissions, both CO₂ and non-CO₂. Therefore, the scope of GHG analysis during this stage will include (1) emissions caused by fuels used in agricultural

machinery; (2) emissions caused by production of raw materials and chemical inputs; (3) emissions caused by N_2O emissions from soil disturbance when N-fertilizer is applied; and (4) emissions associated with the field burning of crop residues especially for the case of sugarcane in Thailand for which more than 50% of cane trash is currently burnt during harvesting (11). GHG emissions associated with manufacturing of farm machinery are negligible when it is distributed over the entire life-time of the machinery (12).

(3) GHG emissions from feedstock processing

After harvest, cassava drying floors and sugar mills are the two stakeholders involved in the bio-ethanol system in Thailand as shown in **Figure 1**. Cassava roots are transported to drying floors which have simple equipment e.g. tractor and chopping machine. Roots are dried naturally by sunlight, therefore, only fuel consumed for the machines is accounted in case of cassava ethanol chain. On the other hand, sugar milling is more complex and has various products and by-products such as raw sugar, refined sugar, molasses and bagasse. In this study, bagasse is assumed to be used to produce steam and electricity. The surplus electricity is sold to the grid and can thus get the credits from avoided conventional electricity production. Molasses, the syrup remaining after the sugar has passed through the centrifuge for the last time in a mill or refinery, is considered as by-product of sugar milling. To evaluate the embodied GHG emissions of molasses, the energy allocation basis can be used in the analysis (13). The energy contents of sugar and molasses are 16.33 and 11.43 MJ/kg, respectively. According to foreground data of sugar mills in Thailand, a ton of sugarcane can yield 105 kg sugar and 46 kg molasses resulting in a factor of 0.24 which can be used to determine the allocation of GHG emissions and credits to molasses (13).

(4) GHG emissions from bio-ethanol conversion (E_{ecv}) and GHG credits obtained from the bio-ethanol production system (E_{cred})

Bio-ethanol conversion involves many energy intensive processes such as ethanol distillation and dehydration. Therefore, at the bio-ethanol plants, fossil fuel and electricity used in the process would be the major sources of GHG emissions. In case of existing cassava and molasses ethanol plants in Thailand, a variety of fuels are used for steam and power generation e.g. imported coal, heavy oil, rice husk, corn cob and bagasse (13, 14). Therefore, GHG emissions originating from this stage could be in a wide range when comparing the plants using fossil fuel and those using biomass as energy source. This study, therefore, makes scenarios to represent this uncertainty.

Also there are various by-products obtained from waste recycling associated with ethanol production that can potentially be used as raw materials in the other processes, e.g. CO_2 , biogas and Dry Distillers Grains with Solubles (DDGS). However, the investment in waste recycling systems depends upon the interest of individual factories. Therefore, several scenarios for waste utilization are investigated with the expectation that maximized waste utilization would provide the largest GHG saving. In the analysis, the credits for by-products from production processes and/or waste utilization are calculated on the basis of system expansion also referred to as “substitution” (15). For example, if the DDGS produced from spent wash was used as animal feed to replace soybean meal, GHG emissions credits would be assigned for the avoided processes linked to the amount of the replaced soybean meal.

(5) GHG emissions from the use of bio-ethanol in vehicles (E_u)

The CO_2 emissions caused by combustion of biofuels in internal combustion engines are assumed to be balanced by the CO_2 fixation during crop growth and hence set to zero in this

study (3, 15). The IPCC's default emission factor for ethanol fuel of about 0.018 g emitted CH₄/MJ ethanol fuel used in cars is included in the analyses (16).

(6) GHG emissions from transport and distribution over the entire life cycle (E_{td})

Road transport by truck is the major mode for bio-ethanol systems in Thailand. For example, the feedstocks such as sugarcane and fresh cassava roots will be directly transported by different types of trucks e.g. 15 t-truck, 21 t-truck, or trailer to sugar mills and cassava drying floors. Then, the processed products such as molasses and dry cassava chips will also be generally transported to ethanol factories by truck. After that, bio-ethanol will be supplied to refinery for blending with conventional gasoline by truck as well. Thus, the whole GHG emissions for raw materials transport and products distribution are estimated from their respective fuel consumption.

(7) GHG emissions from the extraction of input materials (E_{ext})

The embodied GHGs for major input materials including agrochemicals such as N-P-K fertilizers and fuels such as diesel and imported coal are estimated from the amount of input materials based on foreground data multiplied by their respective emission factors based on literature.

S.4 Data sources

Data sources and key parameters used for base case scenarios of bio-ethanol systems in Thailand are shown in **Table S3**. Feedstock productions and yields are the country average data (11, 17). The study refers to primary data of molasses and cassava ethanol production in Thailand from the existing commercial plants (13, 14). For the sugarcane ethanol production which is not yet present in commercial scale as of November 2009, the data on sugarcane ethanol conversion efficiency of about 86 litre ethanol/ton cane is referred from the literature

of the simultaneous production of sugar and ethanol which corresponds to the Thai sugarcane ethanol plants being installed. The production process basically consists of fermentation and distillation/dehydration to produce bioethanol (99.5 wt%) and bagasse is used as fuel for the co-generation system to produce power and steam for ethanol conversion stage.

Table S3 Data sources and key parameters for base case scenarios

Parameters	Cassava ethanol	Molasses ethanol	Sugarcane ethanol	Data sources
Feedstocks cultivation and harvesting				
Crop yields (t/ha)	21.9	69.7		(17)
N-fertilizers input (kg/ha.yr)	47	75		(13, 14, 18)
P-fertilizers input (kg/ha.yr)	22	75		(13, 14, 18)
K-fertilizers input (kg/ha.yr)	56	75		(13, 14, 18)
Agrochemical applied (kg/ha)	2.9	3.7		(13, 14, 18)
Fuel used (Diesel) (L/ha)	44	225		(13, 14, 18)
N ₂ O-EF for fert. application (kg N ₂ O-N / kg N)	0.01	0.01		(5, 19)
CH ₄ -EF for trash burning (kg CH ₄ /kg dm.)		0.0027		(5, 19)
N ₂ O-EF for trash burning (kg N ₂ O-N / kg dm.)		0.00007		(5, 19)
Cane trash (kg dm./kg cane)		0.25		(5, 19)
Burning fraction of cane trash		0.5		(11)
Feedstocks processing				
Dried chips processing (kg roots/kg chips)	2.1			(13)
Molasses production (kg molasses/ton cane)		46.3		(13)
Type of fuel used for processing	Diesel	Bagasse		(13)
Fossil fuel used for processing (L/1000 L ethanol)	18			(13)
Surplus bagasse to electricity (kWh/1000 L ethanol)		679		(13)
Bio-ethanol conversion				
Feedstocks used (kg feedstocks/L ethanol)	2.9	4.6	11.6	(13); (13); (20, 21)
Electricity used	Grid-elec.	In-house	In-house	(13); (13); (20, 21)
Type of fuel used	Coal	Rice husk	Bagasse	(13); (13); (20, 21)
Fossil fuel used (kg fuel/1000L ethanol)	329-669			(13, 14)
Biogas recovery (Cu.m. biogas/1000L ethanol)	80	167	167	(22)
DDGS production (kg DDGS/1000L ethanol)	46			(22)
Surplus bagasses to electricity (kWh/ 1000L ethanol)			126	(22)
Credits for DDGS (kg CO ₂ -eq/kg DDGS)	-0.46			(13)
Credits for Biogas (kg CO ₂ -eq/Cu.m. biogas)	-2.4	-0.45	-0.45	

Credits for surplus bagasse to Grid-elec. (kg CO ₂ -eq/kWh)			-0.72	(13)
Transport and distribution				
Diesel used (L diesel / 1000 Litre ethanol)	26	73	54	(13)
Extraction of input material				
GHG-EF for production of NH ₄ NO ₃ (kg CO ₂ -eq/kg N)	7.1			(5)
GHG-EF for production of urea (kg CO ₂ -eq/kg N)	1.7			(5)
GHG-EF for production of P ₂ O ₅ (kg CO ₂ -eq/ kg P ₂ O ₅)	0.5			(5)
GHG-EF for production of K ₂ O (kg CO ₂ -eq/ kg K ₂ O)	0.4			(5)
GHG-EF for glyphosate (kg CO ₂ -eq/kg glyphosate)	12			(5)
GHG-EF for prod. & use of diesel (kg CO ₂ -eq/L diesel)	2.9			(13)
GHG-EF for grid electricity (kg CO ₂ -eq/kWh)	0.72			(13)

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