Energy and greenhouse gas balances of cassava-based ethanol in Vietnam

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Abstract

The transport sector increasingly contributes to energy consumption and carbon dioxide (CO_2) emissions in Vietnam. Biofuel production has been developed under government policy in an effort to promote energy efficiency and cleaner fuels. However, there have been concerns about biofuel's energy efficiency and greenhouse gas (GHG) reduction ability. This paper investigates energy efficiency and GHG emission of ethanol produced from cassava. Our analysis improves energy and GHG balance accounting on the basis of the opportunity cost principle with consideration of land use change effects in feedstock cultivation. The energy and GHG balances indicate an energy saving of 25.65 mega joules per liter (MJL^{-1}) and a GHG emission saving of 888 gram CO_2 equivalent per liter (gCO_2eL^{-1}). We compare our results with other studies, showing that variations in results are caused by the approaches applied, including land use change effects and CO_2 absorption from cassava cultivations as well as cassava yields, energy–intensity in farming operations, and considerations of by-products.

Keyword

Cassava-based ethanol, energy balance, GHG balance, opportunity cost approach

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1. Introduction

Vietnam is currently a net energy exporter; however, it is projected to be a net energy importer after 2015 [1,2]. The demand for imported fuels grows at an annual rate of 7.19% according to the 2000-2008 statistics [1]. In addition, refined oil constitutes the highest share of total energy consumption at 34% [1].

Like most rapidly developing countries, the transport sector's contribution to total energy consumption and CO_2 emissions in Vietnam is increasing [3-6]. This sector presently accounts for 20% of energy consumption, which has increased at an annual growth rate of 11% throughout 2000-2008 [1]. This contribution is projected to continue growing at an annual rate of 6.4% for the period 2010-2020, ultimately contributing 22% to total energy demand by 2020 [7]. Such growth in fossil-fuel consumption results in corresponding increases in CO_2 emissions, which contribute to climate change through the green-house effect. Based on fossil-fuel combustion in Vietnam, CO_2 emissions from transport accounted for 25% of total CO_2 emissions in 2008 and this figure is expected to increase to 35% and 37% in 2020 and 2030, respectively [5,8]. Thus, when addressing climate change, the transport sector's contribution to CO_2 emissions is a priority and a sector well suited for innovation and promotion of energy efficiency and cleaner fuels [3,5,9].

Biofuel production in Vietnam has been supported by the Government of Vietnam (GoV) under Decision No. 177/2007/QD-TTg of 2007 [10]. The decision includes a development strategy until 2015 and a broader vision for 2025 comprising favorable conditions for research and development (R&D) projects on feedstock and conversion technologies and tax incentives for biofuel investments. The supporting policy focusses on two biofuel products: gasohol (E5) and biodiesel (B5). Gasohol (E5) is a 5% of cassava-based ethanol (E100) blended with 95% gasoline, and biodiesel (B5), a 5% of jatropha-based biodiesel (B100) blended with 95% diesel. The biofuels are planned for use in domestic transportation. Accordingly, annual output targets of biofuel products are 250 thousand tons, equivalent to 1% of fuel demand by 2015; and 1.8 million tons, equivalent to 5% of fuel demand by 2025. Biofuel production has been assigned to economic entities with preferential treatments such as income-tax exemptions and tariff exemptions on materials, machinery and equipment imported for R&D, as well as subsidies for renting land over the next 20 years.

Although there is diversity in biofuel feedstock, cassava and jatropha are the two feedstocks most applicable to Vietnam [11,12]. Jatropha is strategic in GoV planning, whereas cassava is marketdriven based on its availability. Accordingly, as of 2010, four biofuel processing plants have started operations with an annual capacity of 420 thousand tons of E100 in Phu Tho, Quang Nam, Quang Ngai, and Binh Phuoc provinces [13]. While B100 production is currently at the initial stage of jatropha cultivation and processing experiments, cassava based E5 has been sold as fuel since August 2010.

As a non-Annex I country under the Kyoto Protocol, Vietnam is not required to reduce Greenhouse Gas (GHG) emissions. It has, however, signed and ratified the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol and is making substantial efforts to enhance energy efficiency, increase biomass energy generation and institute other Clean Development Mechanism (CDM) projects in the transport and energy sectors [5]. The biofuel solution has, on one hand, been recommended in the literature and promoted under the GoV policy; on the other hand, there exist some uncertainties and concerns about energy efficiency and GHG reduction ability of biofuel substitution [3,9,14].

Energy and GHG balances are used to measure biofuel energy efficiency and GHG emission performance. Calculation of energy and GHG balances takes into account energy and GHG emissions associated with the inputs for ethanol production, distribution and blending, and compares them with those for the equivalent amount of gasoline avoided under biofuel substitution. However, previous studies have not properly considered these two indicators [15-17]. Biofuel production inputs are over-estimated in the standard life cycle assessment (LCA) approach and so are the associated energy and GHG emissions [15]. In addition, the GHG emissions associated with the effect of land use change and land management during feedstock cultivation are often missing [16,17].

This paper aims to investigate the energy and GHG balances of ethanol use and production in the form of E5 substitution for gasoline. We focus on cassava-based ethanol in this paper. Our research contributes to the existing literature on assessment of biofuels by improving energy and GHG balance accounting for biofuel production on the basis of the opportunity cost principle with consideration of the effects of changes in land use and land management in feedstock cultivation. The structure of the paper is as follows: Section 2 presents the status of ethanol production in Vietnam. Section 3 describes the methodology for establishing the energy and GHG balances applied in this study. The results and discussion of energy and GHG balances are presented in section 4. Section 5 contains our conclusion.

2. Cassava-based ethanol production in Vietnam

2.1 Cassava industry in Vietnam

Cassava production has continuously expanded at an annual growth rate of 8.8% and 17.6% in acreage and output respectively, for the period 2000-2009, pushing Vietnam to the 9th and the 3rd place in the world in terms of production and export in 2009 (Table 1) [18,19]. The production concentrates in Vietnam's central and southeast regions with 46.5% of total area and 53.4% of total output in 2009 (Map 1) [18].

Table 1 - Cassava production and exportation in Vietnam.

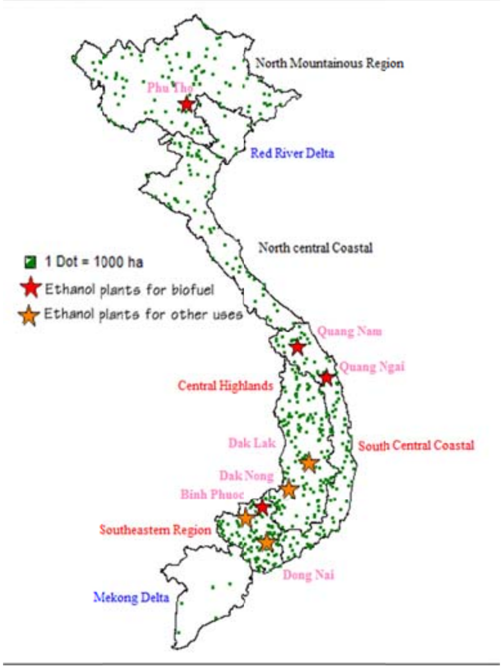
Items	Unit	2000	2005	2006	2007	2008	2009
Area	10^3 ha	238	426	475	496	554	509
Production	10^3 ton	1,986	6,716	7,783	8,193	9,310	8,557
Yield	tonha^{-1}	8.34	15.77	16.39	16.52	16.81	16.81
Exportation							
- Dried chip	10^3ton	135.06	534.05	1,040.66	1,316.56	753.34	2322.70
- Starch	10^3ton	78.00	250.89	467.45	297.13	601.26	905.20

Source: [18-20]

There are no detailed data on cassava utilization in Vietnam. Generally, cassava export of starch and dried chips is estimated to be 42.4% of total production, using conversion ratios from fresh root to dried chips and starch of 2.4 and 4, respectively (The 2011 survey, see section 3 for details on the survey). (Table 1) [21-24]. The remaining cassava has been used domestically as material for industrial processing of sodium glutamate, starch, and animal feed (29.4%), as a source for animal feed, alcohol, cakes, and noodles (16.8%), and as for direct consumption (11.3%) [13]. These estimations do not take into account informal imports through border trade with Cambodia, mostly between Tay Ninh and Binh Phuoc provinces and Kampong Cham and Kratie. Our survey indicates an estimation of 989 thousand tons of fresh root imported in 2010, which accounts for about 10% of the total production for starch processing, animal feed processing and exportation.

2.2 Cassava-based ethanol production in Vietnam

Cassava-based ethanol production rapidly developed under the GoV policies. Before 2007, biofuel production was scattered using catfish fat from processing factories along the Mekong River Delta. Since 2007, under GOV encouragement eight plants have started (as of 2010) with a total annual capacity of 680 thousand tons of ethanol, of which 420 thousand tons from the first four plants are biofuel and the remainder for other uses in alcoholic drinks, cosmetics, pharmaceutics industries and for exportation (Table 2, Map 1). Seven among the eight ethanol plants are located in the Southeast, Central Highlands, and South Central Coastal regions, which now contribute 73% of total cassava production output in Vietnam.



Map 1 - Cassava area and ethanol plants.
Source: [18]

Map 2 - Blending stations.
Source: Survey (2011)

E5 sales commenced at 68 gas stations in 25 cities and provinces in 2011 and will expand to 4,300 stations around the country by 2012 [25]. Currently, the E5 price is 500VND cheaper than that of gasoline. As explained by PetroVietnam, E5 pricing depends on the price of gasoline imported. That the latter is mostly imported and incurs heavy duties has actually caused the price of E5 fluctuate as gasoline.

Table 2 - Cassava-based ethanol production in Vietnam.

No.	**Company name**	**Province**	**Investor**	**Construction period**	**Capacity** (10^6 L year^{-1})	Cassava chip (ton year^{-1})
1. Ethanol plants for biofuel						
1.1	Phu Tho Bio-energy Co.	Phu Tho	PVoil	2009-2011	100	250,000
1.2	Dai Tan ethanol plant, Dong Xanh Co.	Quang Nam	Dong Xanh Co., Bank for investment and development of Vietnam (BIDV)	2007-2009	120	300,000
1.3	Petroleum Centre Zone Ethanol Joint Stock Co. (PCB)	Quang Ngai	Petrosetco (51%), PetroVietnam Finance Corporation (PVFC), Binh Son Petrochemical Refinery (BSR)	2009-2011	100	250,000
1.4	Orient Bio-Fuels Co.	Binh Phuoc	ITOCHU Corporation (49%), PV Oil (29%), LICOGI 16 Co. (22%)	2010-2012	100	250,000
2. Ethanol plants for other products						
2.1	Ethanol DakLak Joint Stock Co.	DakLak	Ethanol Vietnam Joint Stock Co.	2007-2009	66	165,000
2.2	Dai Viet Co.	Dak Nong	Dai Viet Co.	2006-2008	68	170,000
2.3	Quy Nguyen Co.	Binh Phuoc	Quy Nguyen Co.	2010-2011	50	125,000
2.4	Tung Lam Co.	Dong Nai	Tung Lam Co.	2008-2010	76	190,000

Source: Company websites

2.3 Cassava-based ethanol production, distribution and blending process

Cassava-based ethanol production, distribution and blending include three phases: cassava cultivation and processing, conversion to ethanol, and ethanol distribution and blending of fuel.

2.3.1 Cassava cultivation and processing

Cassava in Vietnam is normally planted at the beginning of the rainy season and harvested after 7 to 10 months. Cassava is cultivated mainly in the central highlands, southeast, northern midlands mountainous, and central coast regions, particularly in less developed provinces such as Gia Lai, Tay Ninh, Kon Tum, Binh Thuan, Binh Phuoc, DakLak, Dong Nai, and DakNong (Map 1). Farmers conduct land preparation using tractors and manually perform stem cutting, land hoeing and seeding. The main varieties include KM94, KM140 and KM98-5. Farmers apply both synthetic and organic fertilizers, use low levels of disease control, and produce under rain fed conditions. Weeding and harvesting are also done manually. After harvesting, cassava is sliced and dried in the sun before delivery to ethanol plants in the form of dried chips. The average cassava yield was 17.2 tons of fresh root per ha in 2010 [18].

2.3.2 Ethanol conversion

There are four main sub-processes: milling, liquefaction, saccharification and fermentation, and distillation and dehydration (Figure 1) to produce ethanol from cassava. Besides ethanol, by-products include stillage used as animal feed, biogas as a supplemental heat energy and CO_2 collected for sale. The ethanol processing conversion ratio between dried chips and ethanol applied in this study is 2.6 kgL^{-1}, based on the 2011 survey of ethanol plants in Vietnam, which is has been verified by other studies [21-24].

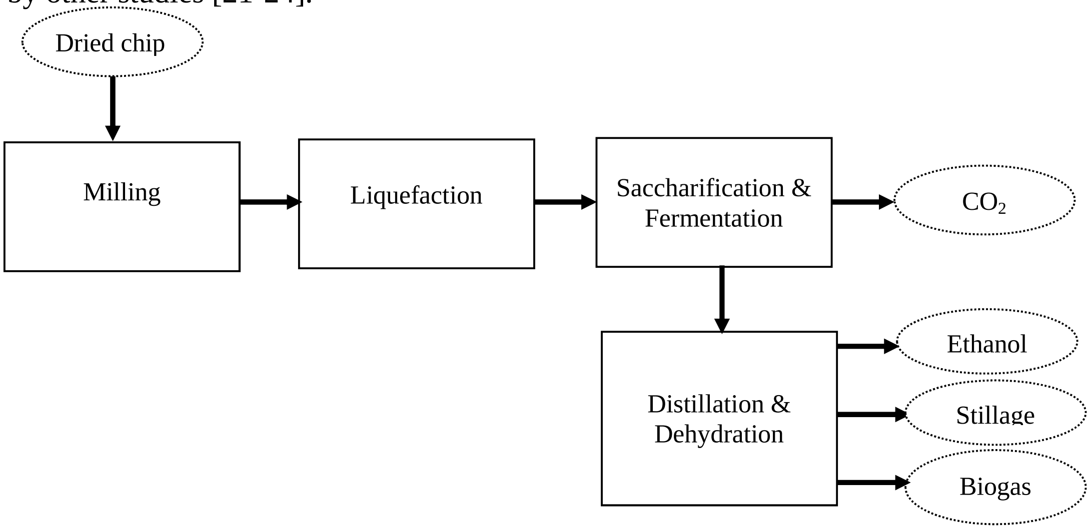


Fig. 1 - Description of cassava-based ethanol conversion.
Source: Survey (2011)

2.3.3 Ethanol blending and distribution

The ethanol is sold to the oil company and delivered to blending stations in fuel warehouses for dispensing and distribution by tanker trucks (Map 2). At the blending station, the tank blending process currently uses pumping machines to deliver gasoline and ethanol into a tank and perform recirculation within the storage tanks. E5 from the blending station is then transported to gas stations for domestic consumption.

3. Methodology

3.1 The opportunity cost approach and substitution ratio

The energy and GHG balance analysis in this paper follows the opportunity cost approach and comparative analysis suggested by Wesseler [15] and Henke et al. [26]. In a comparative static analysis, the energy balance is the difference between the energy for cassava-based ethanol production and the energy content of gasoline which E5 replaces. The GHG balance is the difference between the total GHG emission during cassava-based ethanol production and E5 combustion, and that from the production and combustion of the equivalent amount of gasoline which E5 replaces.

Based on the opportunity cost approach, the calculation of energy and the GHG emission takes into account those associated with the inputs for ethanol production, distribution and blending, but not those for the production of these inputs, as it is clearly explained by Wesseler [15]: “Accounting for the energy used to produce inputs used results in an infinite accounting sequence and hence an infinite amount of production costs. This is obviously not correct”.

For the substitution ratio between ethanol and gasoline, Henke et al. applied the ratio of 0.65:1 on the basis of the energy content [26]. Nguyen et al. argued that in spite of its lower energy value, ethanol has a higher octane value, compression ratio and thus better thermodynamic properties for the internal combustion engine [22]. Therefore, they applied the ratio of 0.89:1 based on fuel combustion in comparison with E10 and gasoline, rather than the energy content. In our study, the substitution ratio is also based on fuel consumption according to a recent report by Ha Noi University of Technology in Vietnam [27]. The report showed that the fuel consumption of E5 improved by 6.37% and 5.18%, respectively for motorcycles and cars in Vietnam in comparison with that of gasoline [26]. This implies an E5 to gasoline substitution ratio of 1: 1.0637 and 1:1.0518 for motorcycles and cars respectively. If we assume that E5 is used by motorcycles and cars at a ratio of 0.7:0.3 then the average substitution ratio is 1:1.06, meaning that the utilization of 1 liter of E5 avoids 1.06 liters of gasoline. This substitution ratio has been verified in other studies [28, 29 and 17].

For our analysis, we conducted a survey in 2011. Our survey of farmers, starch plants, ethanol plants, stakeholders in the cassava supply chain, and provincial key informants was to obtain data on 1) farm input application for energy and GHG calculations, 2) on-site conversion ratios of fresh root to dried chip, starch, and ethanol, 3) ethanol production inputs, and 4) general information on cassava industry and land use change estimation. The areas we chose for the survey are the four top-ten cassava producing provinces: Binh Phuoc, Tay Ninh, Dong Nai and DakNong, with four ethanol plants among the total eight plants.

3.2 Energy balance

The energy balance compares total input energy for ethanol production, distribution and blending with the energy value of gasoline avoided under the E5 substitution. For the input energy, we need information on energy conversion ratios and the amounts of inputs associated with energy generation except for solar energy during cassava cultivation and drying. Figure 2 lists the energy inputs in each phase. For energy conversion ratios, the labour work in agriculture is converted into energy units using the most popular method: “Total Food Consumed” with a ratio of 2.3 MJ hour^{-1} [23,30-33]. The energy conversion ratios of diesel, electricity, steam and biogas (CH_4) are 35.87 MJL^{-1}, 3.6 MJ kwh^{-1}, 3.4 MJ ton^{-1}, and 33.81 MJ:m^{3} respectively [22,23,34,49].

We collected data on human labor for farm operations, diesel for tractors, and energy inputs of electricity, steam, and biogas by-product from the survey. For the cassava production phase, 81 working days ha^{-1} are spent in land clearance, stem cutting, planting, fertilizer application, weeding, harvesting, slicing, and sun-drying. The amount of diesel used in tractors is 15 liters ha^{-1}. For the ethanol conversion phase, the amounts of electricity, steam, and biogas by-product per liter of ethanol are calculated from the annual capacities and energy inputs incurred in one year (2010) for ethanol plants. For the fuel dispensing phase, the amount of electricity needed for pumping is calculated based on a 7.5 horse power engine with a capacity of 60 thousand liters per hour.

The three stages of transportation include transporting 1) dried chips from cassava areas to ethanol plants; 2) ethanol from processing plants to blending stations; and 3) E5 from blending stations to gas stations. To calculate the diesel used in transportation, we need the three national distances, truck capacities, and diesel consumption for each transportation stage (Table 3). Each national distance is averaged with the weights of corresponding three capacities and regional distances.

Table 3- Transportation distances, truck capacities and diesel consumption.

Items	By regions			Vietnam
	North	Central	South	
Ethanol processing capacity				
- 10^6L year^{-1}	100	220	100	420
- %	23.8	52.4	23.8	100
Average distance for one turn (km)				
- Dried chip	100	100	100	100
- Ethanol	120	180	200	170
- E5	50	50	50	50

Items	Average distance for one turn (km)	Truck capacity (10^3L truck^{-1})	Diesel consumption (L 10^2km^{-1})
Dried chip	100	15[1]	35
Ethanol	170	16	35
E5	50	16	35

Source: Survey (2011)
Note: [1]: ton truck^{-1}

A gasoline energy conversion ratio of 32.17 MJL^{-1} is used in this study [34]. With a substitution ratio between E5 and gasoline of 1:1.06, the energy avoided or the reference energy value of 1 liter of E5 is 34.10 MJ; i.e., 32.17 MJL^{-1} of gasoline multiplied by 1.06. The energy balance for 1 liter of ethanol is the difference between the reference energy value and the total energy expended for cassava production, ethanol conversion, blending and distribution of ethanol.

[redacted]

3.3 GHG balance

In the same manner as energy balance analysis, the GHG balance is the difference between total GHG emission from ethanol production, distribution and dispensing, and E5 utilization and that from production and consumption of gasoline avoided by the E5 substitute. The GHG emissions include the phases of cassava production, ethanol conversion, ethanol distribution and dispensing as well as the phase of E5 combustion (Figure 2). The GHG emission of E5 combustion and the GHG emission factors (EFs) of gasoline extraction, refinery, and consumption are derived from the literature [35,36]. The GHGs considered are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) with respective global warning potential (GWP) factors of 1, 21, and 310 [37].

In the first phase i.e. the cassava cultivation, GHG emissions are calculated based on IPCC (2006) and the UNFCCC/CCNUCC (2004) guidelines [37,38]. Accordingly, five GHG emission sources are considered, namely land clearance, field burning of biomass, change in soil carbon stock due to land use change, change in land management, and diesel consumption in agricultural operation. A detailed explanation for calculation of GHG emissions and parameters are presented in the supplementary information 1 (SI.1).

For land clearance and field burning emissions, the land area is calculated from the cassava yield in 2010 and ethanol conversion ratio, assuming that cassava needed for ethanol production comes wholly from domestic cultivation. The weight of cassava residues is estimated from the harvest index reported by Hoang et al. [39]. In terms of biomass stock, cassava residue ratios actually burnt and returned to soil are 79% and 21% respectively.

For land use change, the CO_2 emission from soil carbon stock change is calculated as the multiplication of the changes in soil carbon stocks and the areas shifting to cassava from either forest or grass land. Each area equals the percentage of land use change from either forest land or grass land multiplied by the total cassava area. These two percentages (34.05% and 26.03% of land use change from forest or grass land to cassava) are derived from the survey in the fourteen leading cassava producing provinces with an average of 66% cassava area in 2005-2009 (SI.2).

The emission from diesel for tractors equals the emission factor of diesel combustion multiplied by the amount of diesel (15 liters ha^{-1}). For the N_2O emission, we need the amounts of 1) organic fertilizer nitrogen; 2) synthetic fertilizer nitrogen; and 3) nitrogen in cassava residue. The amount of organic fertiliser nitrogen is calculated by the average amount of manure applied by farmers multiplied by the manure nitrogen content of 0.0032 suggested in [40]. For synthetic fertilizers, since Vietnamese farmers have applied both synthetic fertilizers -the so-called NPKs, and the single nutrients, we calculate the nitrogen amount from both applications. Nitrogen content in dry matter of cassava residue is 0.015 [41].

Cassava cultivation generates GHG emissions through the five abovementioned sources. However, this plant also absorbs CO_2 through its photosynthesis and captures carbon into its roots and foliage dry matters. Some studies have actually reported a positive effect of CO_2 absorption [24,42]. To measure this effect, we use the change in carbon sequestration resulting from land use change for cassava cultivation to be the amount of carbon sequestration associated with the shift of grass land to cassava, assuming that there is no change in carbon sequestration for shifting from forest and other crops to cassava. Carbon sequestration is estimated based on the carbon content in cassava dry matter and the weights of cassava foliage and roots, following the guidelines in Pearson et al. [43] (SI.3). Due to the unavailability of carbon content in cassava dry matter, the default value of carbon content in biomass dry matter suggested by the IPCC (2006) is utilized in this study.

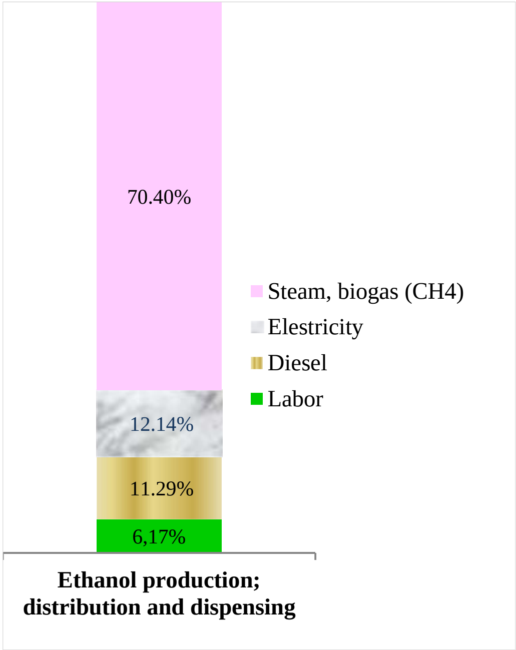
In the second phase, the ethanol conversion process eventually gains certified emission reductions (CERs) as net emission reductions and emissions in conversion under the CDM performance of biogas. Besides, advances in technology allow ethanol plants to collect CO_2 from the process. Thus, the positive effect on GHG emission is the amount of CO_2 collected and CERs gained by the processors.

In the phase of distribution and dispensing, GHG emissions are from the use of electricity for pumping and the use of diesel for transportation. These are estimated by multiplying the EFs of electricity and diesel and their amounts mentioned in section 3.2.

4. Results and discussion

4.1 Energy balance

The energy inputs include steam, diesel, electricity, and labor in farm operations (Figure 3). The biogas by-product in the form of methane (CH_4) is used for steam production. Steam is the most important component accounting for 70.40% of total energy, including the energy contribution produced by biogas. Labor contributes the lowest portion, i.e. 6.17%. Diesel’s contribution is 11.29%, of which 80% is used for transportation and 20% is for tractor operations (Table 4). Electricity accounts for 12.14% of total energy and most of it is used in the ethanol conversion phase.



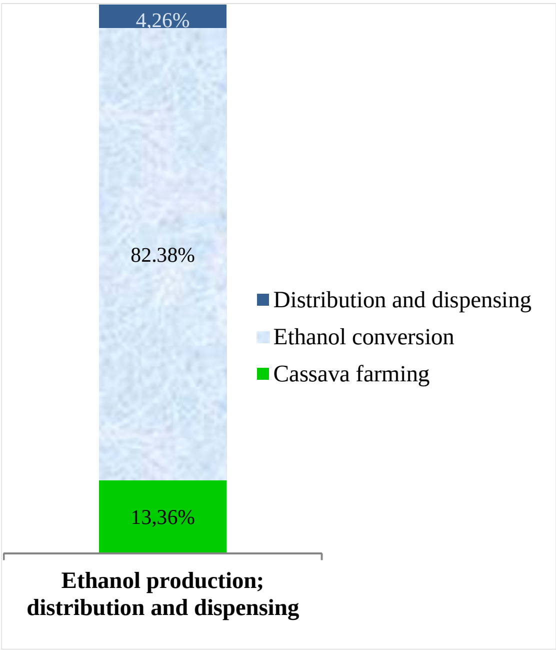


Fig. 3 - Energy by factors.
Source: Authors' calculation

Fig. 4 - Energy by phases.
Source: Authors' calculation

Regarding energy allocation along the three phases, the most energy consuming phase is the ethanol conversion, amounting to 82.38% of total energy expended (Figure 4, Table 4). Cassava production and transportation account for 13.36% of total energy. The distribution and dispensing phase incurs 4.26% of total energy, mostly for the use of diesel for transportation.

With a reference value of 34.09 MJ of E5, every liter of ethanol produced and dispensed saves 25.65 MJ, equivalent to the energy value of 0.8 liter of gasoline. With an ethanol capacity of 420 million liters per year, Vietnam would save 334 million liters of gasoline, or 10.773 billion MJ per year with E5 substitution. The ethanol plants are well located around cassava supply areas to reduce transportation costs, and almost all ethanol plants utilize biogas by-product to supplement energy usage in the conversion process. Opportunities for input energy reduction could lie in improvements in cassava yield, and shorter distances for ethanol and E5 transportation with more blending stations and gas stations. Following this positive result, if the cassava-based ethanol market is properly designed in Vietnam, a fossil fuel energy saving should be promising in the future.

Table 4 - Energy balance of cassava-based ethanol in Vietnam.

Energy inputs	Inputs		Amount (Unit $10^3 L^{-1}$)	Energy (MJ $10^3 L^{-1}$)	%
	Unit	Ratio (MJ $Unit^{-1}$)			
Total				**8,438.55**	**100**
Cassava farming				***1,127.16***	***13.36***
- Labor	man-hours	2.30	226.39	520.70	
- Diesel for tractor operation	liter	35.87	5.24	187.98	
- Diesel for transportation	liter	35.87	11.67	418.48	
Ethanol conversion				***6,952.16***	***82.38***
- Electricity	kwh	3.60	280.96	1,011.46	
- Steam	ton	3.40	3,040.00	10,336.00	
- Biogas cogeneration (CH_4)	m^3	33.81	130.00	(4,395.30)	
Distribution and dispensing				***359.23***	***4.26***
- Electricity	kwh	3.60	3.68	13.23	
- Diesel for distribution	liter	35.87	9.65	346.00	

Energy balance = 34.09 x 1,000 - 8,438.55 = 25,651.45 MJ $10^3 L^{-1}$

Source: Authors' calculation

4.2 Energy balance of cassava-based ethanol: a comparison with other studies

The estimation of GHG and energy balances can potentially produce variable results depending on 1) the types of biofuel feedstock; 2) the specific application of energy inputs in farming operations; 3) feedstock yields; and 4) the energy intensity level of the ethanol industry [26]. Our analysis focuses on cassava-based ethanol, keeping the first factor constant. The three remaining factors are examined in the 2011 survey. The changeability of these factors possibly causes result variations in comparison with other studies. Besides, the different application of the opportunity cost approach in this study induces a specific result for Vietnam compared to other country based studies.

For comparison purpose, our attention is paid to the studies on energy and GHG balance analysis in the same line of cassava-based ethanol. A comparison of energy balances among different studies is presented in Table 5. The energy balance is the difference between the reference value and input energy. The reference value is explained by the energy base of either gasoline or ethanol itself with the base of 1. Our study uses the energy base of gasoline with the fuel consumption-based substitution ratio of 1.06 which better suits the opportunity cost approach and is tested recently in 2009.

Table 5 - Energy balance of cassava-based ethanol: a comparison with other studies.

Country and sources	Energy inputs ($MJ\ L^{-1}$)	Substitution ratio (time)	Energy of gasoline/ethanol[4] ($MJ\ L^{-1}$)	Energy balance ($MJ\ L^{-1}$)
China [31]	13.71	1.00	21.19[4]	7.48
China [24]	16.59	1.00	21.18[4]	4.60
Thailand [22]	12.06	0.89	38.70	22.38
Vietnam	8.44	1.06	32.17	25.65

Source: [22,24,31] and authors' calculation

Unlike previous studies, our study improves the energy balance accounting for ethanol production using opportunity cost principle, rather than the LCA approach which induces infinite accounting. Following the LCA, the calculation in other studies includes not only the energy of inputs but also the energy for the production and transportation of these inputs, and even "losses during electricity generation" [22, p.4]. To prevent infinite accounting, some limitations have been proposed in the LCA to exclude the energies for building the ethanol facilities and producing the transportation equipment due to its little amount per liter of ethanol, outdated available data, and preclusion of a tremendous amount of data [31]**.** Our study excludes these sources of energy as they are not associated with direct energy generation for ethanol production. This avoids the problem of infinite accounting of input energy because at its core the approach is not based on the resources used to get an ethanol based fuel source but rather what else we could have done with them, for example, fossil fuel gasoline production. In this sense, the input energy only have value based on the fact that we can use them to make ethanol-based fuels and this is similar to the value of pure fossil fuel-based gasoline.

There are some differences in cassava fresh root yields . Our study applied the average national fresh root yield in 2010 of 17.17 ton ha^{-1} while the others used much higher yields ranging from 27 to 39 ton ha^{-1} for a specific provincial site [31], under the author's assumption [24], or from the literature [22]. Given constant farm input energy, the higher yield is applied, the less energy is spent on per liter of ethanol. The differences in labour energy are explained by the choice of working days incurred and conversion ratios. Our study applied 81 working days ha^{-1} equivalent to 648 hours ha^{-1} while the figures in [31] and [22] are 1,920 and 433 hours ha^{-1}, respectively. A conversion ratio of 2.3 MJ $hour^{-1}$ is mostly used, while 12.1 MJ $hour^{-1}$ is applied in [22]. As for the biogas utilization for steam production, the energy intensity of ethanol industry is not very different among different studies.

4.3 GHG balance

The results of GHG balance are described in Table 7. The literature has mentioned the lack of indirect effects of feedstock plantations on GHG emissions, which is a main cause of suspicions in GHG emission saving contributed by biofuels [3,9,16]. In our study, the indirect effects of the feedstock plantation on GHG are considered including the change in carbon sequestration contributed by cassava cultivations.

Table 6 - GHG balance of cassava-based ethanol in Vietnam.

Items	**Exhaust rate (g L^{-1})**	**Emission (gCO2e L^{-1})**
1. GHG emission from ethanol production		***(347.76)***[5]
Cassava cultivation		1,033.87
- CO_2 emission from land clearance		1,358.83
- CH_4, N_2O emission from field burning		125.16
- CO_2 emission from land use change		652.88
- N_2O emission from change land management		260.83
- Diesel consumption		15.36
- Change in carbon sequestration		(1,379.20)
Ethanol conversion (CERs)		(1,405.00)
Distribution and dispensing		23.37
- Electricity		1.56
- Diesel for transportation		21.81
2. GHG emission from E5 combustion		***2,369.18***
- CH_4	0.10	2.13
- N_2O	0.15	45.57
- CO_2	2,321.47	2,321.47
3. ***GHG emission from gasoline extraction and refinery***		***308.44***
- CH_4	0.55	11.65
- CO_2	296.78	296.78
4. GHG emission from gasoline combustion		***2,436.35***
- CH_4	0.10	2.12
- N_2O	0.32	97.94
- CO_2	2,336.28	2,336.28
GHG balance = (2,436.35 + 308.44) x 1.06 – (2,369.18 -347.76)		**(888.05)**

Source: IDIADA (2003), Lewis CA. (1997), survey (2010), and authors' calculation
Note: [5]: the figures in brackets mean GHG emission savings

In terms of GHG emission allocation, ethanol production, distribution and dispensing would result in a GHG saving of 347.76 $gCO_2e\ L^{-1}$. The highest GHG emission incurred in agricultural activities is 2,413 $gCO_2e\ L^{-1}$. This result is reconciled with GHG emission reduction from carbon sequestration of 1,379 $gCO_2e\ L^{-1}$, resulting in an overall GHG emission in cassava cultivations of

1,034 $gCO_2e\ L^{-1}$. With advanced technologies, the ethanol conversion phase leads to a GHG emission reduction of 1,405 $gCO_2e\ L^{-1}$ from the CERs and CO_2 collected from the fermentation process. The ethanol distribution and dispensing phase has a small increase in GHG emissions, amounting to 23.37 $gCO_2e\ L^{-1}$. The EF of gasoline production is reported to be 308.44 $gCO_2e\ L^{-1}$ [36]. The combustion emission of E5 is 5% lower than that of gasoline [35].

Eventually, the cassava-based ethanol production, distribution, dispensing, and utilization would result in a GHG saving of 888 $gCO_2e\ L^{-1}$. With an ethanol capacity of 420 million liter per year, Vietnam would achieve a saving of 373 million tons of CO_2e per year with E5 substitution. The opportunities for further GHG savings lie in improved agricultural practices. In particular, cassava residues should be returned to the soil at higher ratios and the burning of fields avoided. In addition, intensive cassava cultivation should be encouraged with sustainable land management and a gradual shift from synthetic to organic fertilizer to reduce emission of nitrogen-oxide.

4.4 GHG balance of cassava-based ethanol: a comparison with other studies

The GHG balance comparison is presented in Table 7. The GHG balance is explained by 1) GHG emissions from gasoline production and combustion, 2) the substitution ratio of 1 liter of E5, 3) GHG emission from gasohol combustion, and more importantly, 4) GHG emissions from ethanol inputs. The substitution ratio varies from 0.65 to 1.06, inducing its different products with the GHG emission from gasoline production and consumption in the studies of [24], [42], [22] and our study. Leng et al. (2008) did not include this product in their GHG balance analysis but separately made a comparison of the emissions of gasohol and gasoline combustion. The GHG emission of gasohol combustion varies depending on the specific types of gasohol; e.g., E100 in [42,44], E10 in [24] and E5 in our study. Specially, the case [44] only included the CH_4 emission in ethanol GHG emission with the assumption that CO_2 emission from gasohol combustion is balanced with CO_2 absorption during cassava cultivation, explaining an inaccurately small amount of ethanol emission.

Variations in GHG emissions from ethanol inputs could appear from four aspects: a) different approaches such as the LCA approach in other studies or the opportunity cost approach in our study; b) the three factors mentioned in energy balance analysis with the most significant being ethanol processing technology and by-product utilization; c) inclusion of changes in land use and management; and d) the inclusion of CO_2 absorption from cassava cultivations.

Table 7- GHG balance of cassava-based ethanol: a comparison with other studies.

Sources	Emission inputs (g CO_2e L^{-1})	Emission of gasohol consumption (g CO_2e L^{-1})	Substitution ratio (time)	Emission of gasoline production and consumption (g CO_2e L^{-1})	GHG balance (g CO_2e L^{-1})
China [24]	15,483	1,769[6]	1.00		13,714
China [42]	21	1,516[7]	0.65	2,826	(300)[5]
Thailand [22]	964	-	0.89	2,918	(1,633)
Thailand [44]	1,328-6,437[9]	8[7]	0.65	2,900	(549) -4,560
Vietnam	(348)	2,369[8]	1.06	2,745	(888)

Source: [22,24,42,44] and authors' calculation

Note: [5]: the figures in brackets mean GHG emission savings; [6-8]: Emission of E10, E100, and E5 consumption respectively; [9]: Scenarios with alternative options of by-product utilization and land use change from either forest or grass land to cassava, resulting in a range of GHG emissions

Different from other studies which applied LCA, our study takes the opportunity cost approach. Therefore, we exclude those sources not associated with the ethanol production, distribution and dispensing like the production of inputs: fertilizers, pesticides, and fossil fuel. This prevents a huge amount of emissions irrelevant to ethanol production and infinite accounting if the LCA would be thoroughly implemented. This explains the high GHG emissions in the studies of [24] and [44].

Second, among three factors mentioned by Henke et al., the most significant is the ethanol processing technology and by-product utilization [17, 44-47]. The GHG balance has become more positive with technology improvements and GHG emission credits from by-product utilization [45-47]. Our study is in the same line of [47], where advanced technologies with the utilisation of biogas by-product are considered. The Thailand case considered GHG emission credits assigned for the production process avoided for the utilisation of by-products. For example, the electricity generated from biogas was assigned to earn GHG emission credit equal to that from the electricity production avoided. So were other by-products like animal feed. However, these GHG emission credits are obviously over-estimated in the LCA, inducing the over-estimation of the GHG emission earning. More properly in our study, the utilization of biogas by-product in steam generation reduces the input energy and obtains net CERs after reconciliation with other GHG emissions during the whole ethanol production process. Therefore, GHG emission in the ethanol conversion phase is negative in our study. Besides, energy–intensity in farming operations and cassava yields also affect GHG emission per unit of ethanol through the emission from fuel consumption by agricultural machinery.

Third, our study considers the GHG emissions from changes in land use and management as [47] . The shift of either forest or grass land to cassava cropping changes the carbon soil stock and the corresponding CO_2 emission; and nitrogen fertilizer application is GHG-intensive due to N_2O emission through leaching and nitrogen volatilized in cassava farming.

Fourth, our study includes the CO_2 absorption from cassava cultivations as [42] and [47]. While the CO_2 absorption was either assumed to be equal to the gasohol combustion in [47] or directly measured as the amount of CO_2 photosynthesis in [42], it is properly calculated for the change in carbon sequestration due to land use change in our study.

On the whole, a wide range of total GHG emission from ethanol production, distribution and blending can be explained by the four aspects. It is possibly unduly high in study [24] with inclusion of emissions from fossil fuel production and distribution, and omission of CO_2 absorption or too low in studies such as [42] due to the direct inaccurate use of the amount of CO_2 photosynthesis. Our study reconciles CO_2 absorption in the form of changes in carbon sequestration with input emissions and considers the CERs earned during ethanol conversion. This explains a GHG emission saving in the whole process.

5. Conclusions

Our study shows that the energy balance from cassava-based ethanol provides an energy saving of 25.65 MJ L^{-1} in comparison to standard fossil fuel. The most energy consuming phase lies in ethanol conversion with 82.38% of total energy. The opportunities for energy efficiency improvement are in increased cassava yields, and shorter transportation distances with more blending stations and gas stations. The GHG balance analysis shows that every liter of cassava-based ethanol production, distribution, dispensing, and utilization would result in a GHG saving of 888 gCO_2e. The opportunities for further GHG savings are in a) higher ratios of the cassava residues returned to soil and a decrease in field burning; b) intensive cassava cultivation with sustainable land management and reduction in nitrogen fertilizer application. The comparisons of energy and GHG balances with other studies shows that our study gains higher energy balance and a GHG saving and that the variations in results are due to the approaches applied; the coverage of land use change effects and CO_2 absorption from cassava cultivations; as well as cassava yields, energy–intensity in farming operations, and by-product analyses.

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