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Economic viability of large-scale cassava cultivation on a post-mining area for bioethanol production in Vietnam

Feasibility study

Imprint

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1 Introduction

In the last 30 years Vietnam's economy has grown rapidly leading to an increasing energy demand. The country's energy supply mainly consists of fossil fuels like coal, oil and natural gas. This leads to increasing environmental problems and contributes to climate change. In recent years, renewable energy sources like wind and water power as well as biofuels and waste have become more and more important and the potential for expansion is high due to Vietnams geographic and climatic characteristics. Especially biofuels can stabilise the energy system when wind power and solar energy are temporarily not available and can provide energy for those households that are not connected to the power grid, because it is locally available and storable. Furthermore, sustainably produced biofuels contribute to the decrease of greenhouse gas (GHG) emissions. For example, in most of the cases, biofuels produce less GHG emissions in comparison with fossil fuels. To further increase the share of renewable energy sources in Vietnams energy supply the government introduced different policies like obligating the blending with bioethanol. However, the expansion of producing energy crops for generating bioethanol demands large areas of agricultural land. Therefore, it can lead to land use changes (LUC) like deforestation and might compete with food production, increasing food prices, and threatening food security. Moreover, arable land becomes increasingly scarce due to urbanisation and soil degradation. As a consequence, there is a need for sustainable production options for bioethanol in Vietnam.

The two-phase project "Climate Protection through Energy Plants" (CPEP) in Vietnam wants to fill this gap by cultivating cassava for bioethanol production on former mining sites, which are not suitable for food production due to poor soil quality and heavy metal contamination. Mining companies in Vietnam are obliged to recultivate former mining sites. So, the projects approach gives mining companies a sustainable recultivation solution and the opportunity to increase their income by selling the cassava plants to bioethanol factories. Within the first project phase (CPEP 1), a cultivation pilot of cassava has been conducted on a post-mining site in Thai Nguyen Province. The preliminary results of this project and available studies on bioethanol have revealed the feasibility and potential benefits of cultivating cassava on former mining sites for both bioethanol development and sustainable recultivation. For example, the CPEP1 results show that fuel produced with bioethanol from cassava cultivated on former mining sites can save up to 49.3 percent of CO_{2eq} emissions compared to the use of conventional RON92 gasoline. As part of the second phase project (CPEP 2), this feasibility study evaluates the economic viability of large-scale cassava cultivation on a post-mining area in Lam Dong Province for bioethanol production.

It first assesses the current legislation in Vietnam to analyse its contribution in promoting biofuels. It then summarises Vietnam's energy supply and bioethanol market to assess whether the country's economic infrastructure is sufficient to scale up the production of bioethanol from cassava. Afterwards, the cassava production on the test-site in Lam Dong Province is summarised and compared with average regional yields. A life cycle analysis (LCA) is then used to assess the potential GHG savings from the use of bioethanol from cassava cultivated on the Lam Dong test site. Finally, the potential co-benefits of cultivating cassava on former mining sites and the potential for scaling up the production are discussed before the final conclusions are drawn.

2 Current legislation on biofuel development in Vietnam

2.1 Policies and legal regulations related to climate change, green economy and energy transition

In Vietnam, in recent years, the development of renewable energy in general, including biofuel development, has been promoted through resolutions, documents, laws and policies as well as programs, action plans and projects. The content of biofuel development has been integrated into policy documents on climate change, renewable energy development in general and the development of the transportation industry. The following section summarizes the development of legislation on biofuels in Vietnam.

Article 19 of Law No. 50/2010/QH12 on efficient and economical use of energy[1] encourages the exploitation and expansion of application of liquefied petroleum gas, natural gas, electricity, mixed fuels, and alternative biofuels to replace gasoline and oil. Reasonable development according to planning of raw material crop areas for biofuel production has also been stipulated in Article 24 on reducing electricity loss and using renewable energy in agricultural and rural production of the law on efficient energy use. According to Article 25, the Ministry of Agriculture and Rural Development is responsible for presiding with relevant agencies to develop a plan for growing raw materials for biofuel production and submit it to the Prime Minister for approval and the People's Committee. The province is responsible for directing the implementation of planning for planting areas for raw materials for biofuel production.

In 2015, the Vietnam Renewable Energy Development Strategy to 2030, with an outlook up to 2050, was approved by Decision No. 2068/QD-TTg dated November 25th, 2015. One of the objectives of this Strategy is to increase the production of biofuels to meet 5, 13 and 25 percent of the transport sector's fuel demand in 2020, 2030 and 2050, respectively. According to the orientation of developing and using biofuel sources from now to 2030, it is necessary to increase resources for the activities of research, development and investigation, planning biofuel development areas and developing pilot projects on biofuel to replace a part of the nation's petroleum demand. In addition, it is required to support the investment in pilot projects to produce 2nd and 3rd generation biofuels, using non-food raw materials. In order to achieve the above goals, one of the solutions to increase the rate of development and use of renewable energy sources proposed in the Strategy is to encourage the development and use of clean and high efficient biofuels and develop energy crops. Petroleum businesses must combine the sale of bio-liquid fuel that meets national standards in the local fuel sales system. Every year, the Ministry of Industry and Trade issues specific regulations on the minimum percentage of bio-liquid fuel that petroleum businesses must sell in localities.

Resolution No. 55-NQ/TW of the Communist Party of Vietnam on the orientation of Vietnam's National Energy Development Strategy to 2030, vision to 2045[2] was issued on February 11th, 2020. One of the specific goals set out in Resolution No. 55-NQ/TW is that the proportion of renewable energy sources in the total primary energy supply will reach about 15-20 percent by 2030 and 25-30 percent by year 2045.

The National Strategy on Green Growth for the period 2021 - 2030, vision 2050 was approved in Decision No. 1658/QD-TTG on October 1st 2021[3] (referred to as VGGS). One of the specific goals of the Green Growth Strategy is for the proportion of renewable energy in total primary energy supply to reach 15-20 percent by 2030 and 25-30 percent by 2050. To achieve the above goal, the Green Growth Strategy has set out an

[1] Government of Vietnam (2010)
[2] Government of Vietnam (2020)
[3] Government of Vietnam (2021)

orientation to transform the energy structure in the direction of reducing dependence on fossil energy, promoting effective exploitation and increasing the proportion of renewable energy sources and new energy in production and consumption of the national energy.

Vietnam has updated its **Nationally Determined Contribution**[4] (NDC) under the United Nations Framework Convention on Climate Change (UNFCCC) in 2022. The updated NDC has shown greater ambition of the Vietnamese Government compared to the NDC 2020, particularly, the unconditional Contributions have increased from 9 percent to 16 percent and Conditional Contributions have increased from 27 percent to 44 percent. The Vietnamese Government also allocated the national emissions reduction into five sectors, including: energy, industrial processes, agriculture, land use, land use change and forestry (LULUCF) and waste. In the energy sector, the updated NDC in 2022 aims to reduce the GHG emissions by domestic efforts by 7 percent compared to the "Business as Usual Scenario" (BAU) by 2030 and that target will increase up to 24.4 percent compared to the BAU when receiving the international supports. The implementation of NDC 2022 is consistent with the net zero emissions target in the National Strategy on Climate Change for the period up to 2050 and measures to implement the methane emission reduction plan.

The Action program on green energy conversion, carbon and methane emission reduction of the transportation sector was approved in Decision No. 876/QD-TTg on 22 July 2022 (referred to as the Green Energy Transition Action Program) with the overall goal of developing a green transportation system towards the goal of net greenhouse gas emissions reaching "zero" by 2050. Implementing green energy conversion, including biofuels, in the transportation industry has been integrated into the perspective, goals, green energy conversion roadmap and solution tasks of the Program. Directly related to biofuel development, one of the activities that needs to be carried out in the period 2022-2030 is to expand the mixing and use of 100 percent E5 gasoline for road motor vehicles.

The National Strategy on Climate Change for the period up to 2050 (2022) was approved in Decision No. 896/QD-TTg dated 26 July 2022.[5] Regarding the goal of reducing GHG emissions, this Strategy has set a net emission target of "zero" by 2050, which sets specific GHG emission reduction targets for the following sectors: energy, agriculture, land use, land use change and forestry (LULUCF) as well as industrial processes and waste. For the energy sector, this Strategy sets a target that by 2030, GHG emissions from the energy sector will be reduced by 33 percent, with emissions not exceeding 457 million tons of CO_2 equivalent compared to the normal development scenario (BAU). By 2050 the GHG emissions should be reduced by 92 percent, not exceeding 101 million tons of CO_2eq compared to the BAU Scenario. In order to achieve the above goal in the energy sector, the Strategy has proposed specific tasks and solutions. Regarding energy supply, the Strategy sets a goal that by 2030, the proportion of renewable energy sources, including biomass, will account for at least 33 percent of total electricity generation and this proportion will increase to 2050. Regarding energy use, the Strategy also provides solutions to develop and implement a roadmap for converting to clean fuel for vehicles.

The National Power Development Plan for the period 2021 - 2030, with a vision to 2050 (referred to as Power Development Plan VIII) was approved in Decision No. 500/QD-TTg dated15 May 2023 of the Prime Minister. One of the goals of the Power Development Plan VIII on equitable energy transition is to strongly develop renewable energy sources for electricity production, reaching a rate of about 31 to 39 percent by 2030, aiming for a 47 percent renewable energy share provided that commitments under the Political Declaration establishing the Just Energy Transition Partnership (JETP) with Vietnam are fully recognized and practically

[4] Government of Vietnam (2022b)
[5] Government of Vietnam (2022a)

implemented by international partners. In orientation to 2050, the proportion of renewable energy will reach 68-72 percent. The Power Development Plan VIII has closely followed solutions to reduce greenhouse gas emissions to achieve net zero emissions by 2050 as committed by the Prime Minister at the COP26 Conference. Accordingly, the Ministry of Industry and Trade proposes not to build new coal power plants from 2030. Coal power plants with a lifespan of over 40 years will be considered to stop operating or convert to biomass power plants and ammonia before 2050. In addition, the Power Development Plan VIII also encourages the development of power sources using renewable energy at reasonable prices associated with ensuring safe operation of the power system and the overall efficiency of the electricity system.

The Project to implement the political declaration establishing a just energy transition partnership[6] was issued by the Prime Minister in Decision No. 1009/QD-TTg on 31 August 2023. The project's goal is to reach 47 percent of renewable energy by 2030 and 80-85 percent of total primary energy by 2050. Some key direct and indirect tasks related to the development of biofuels include promoting the conversion of coal power to clean energy (including biomass power) and green energy conversion, reducing GHG emissions of the transportation sector, for instance through the use of biofuels. Table 1 summarises the mitigation targets of Vietnam's National Climate Change Strategy.

Table 1: Mitigation targets of Vietnam´s National Strategy on Climate Change

Sector	2030		2050	
	% GHG reductions compared to the BAU	GHG emissions ($MtCO_2$tđ)	% GHG reductions compared to the BAU	GHG emissions ($MtCO_2$tđ)
Energy	-32.6%	≤457	-91.6%	≤101
Agriculture	-43.0%	≤63.9	-63.1%	≤56
LULUCF	-70% emissions +20% removals	≥-95	-90% reductions + 30% removals	≥-185
Waste	-60.7%	≤18	-90.7%	≤8
Industrial processes	-38.3%	≤86	-84.8%	≤20
Total	**-43.5%**		Net zero emissions	0

[6] Government of Vietnam (2023)

2.2 Policies and legal regulations on biofuel development

In Vietnam, there is the goal of developing biofuel as a new, renewable form of energy to partially replace traditional fossil fuels, contributing to ensuring energy security and environmental sustainability. In 2007, the Prime Minister approved Decision No. 177/2007/QD-TTg on the "**Scheme on Development of Biofuels up to 2015 with the Vision to 2025**" with the aim of developing biofuels as a new and renewable energy source to partially replace conventional fossil fuels, to assure energy security and to contribute to climate and environmental protection. According to Decision 177/2007 / QD-TTg, the output of ethanol and biodiesel will reach 1.8 million tons by 2025. The government has outlined solutions that focus on research and development, encouraging investments in biofuel technologies, building the potential for biofuel development through enhancing human resources, modernizing equipment and increasing international communication and technology transfer.

Decision No. 53/2012/QD-TTg dated 22 November 2012 of the Prime Minister also established a roadmap for implementing the biofuel mixing ratio with traditional fuels. From 1 December 2015 and 2017, the gasoline produced, blended and traded for use by road motor vehicles for nationwide consumption should be E5 and E10 gasoline, respectively.

In 2017, a number of subsequent decisions were adopted to strengthen and accelerate the progress of implementing the roadmap (Decision No. 255/TB-VPCP, Decision No. 6196/BCT-TTTN, Decision No. 1127/PLX-KTXD, Decision No. 3055/QD-BCT, Decision No. 1195/PLX-HĐQT and Directive No. 11/CTBCT). As a result, from the beginning of 2018, E5 gasoline must be sold nationwide and must replace regular gasoline (A92 or RON 92). In addition, the use of E10 gasoline in 2018 has been decided.

Notification No. 255/TB-VPCP on "Conclusion of Vice Prime Minister Trinh Dinh Dong at the meeting on implementation of the project of Development of biofuels and a roadmap for the application of biofuel mixing ratio" was approved on 6 June 2021. According to the notification, the Vietnamese Government only allowed two types of gasoline, i.e. RON 92 and E5 RON92, to be utilized until the end of 31 December, 2017. Since 1 January 2018, only E5 RON 92 and RON 95 are allowed to be produced and traded in order to contribute to the goal of energy security, gradually reducing the dependence on fossil fuel, improving the environment, and at the same time implementing the commitments of the Government of Vietnam to the global mitigation efforts, contributing to generating sustainable income for the agricultural sector and promoting the restructuring of the agricultural sector.

After the strong commitment to reduce net emissions to "Net Zero" by 2050 at COP26 Conference, the Government has reviewed the system of relevant legal documents and regulations, including policy mechanisms for biofuels in Vietnam. The Ministry of Industry and Trade and other ministries immediately organized implementation in accordance with the tasks specified in Decision No. 888/QD-TTg dated 25 July 2022 of the Prime Minister approving the Project on tasks and solutions. As results the goal was set to use 100 percent E5 gasoline in the transportation sector by 2030.

The Ministry of Science and Technology **issued the National Technical Regulations on gasoline, diesel fuel and biofuels in Circular No. 16/2022/TT-BKHCN** on December 15th 2022 (QCVN 01 :2022/BKHCN), which stipulates limits on technical criteria related to safety, health, environment and quality requirements for gasoline, diesel and fuel. From 15 June 2023, gasoline, diesel and biofuel products produced, mixed, imported and distributed must meet the regulations in QCVN 01:2022/BKHCN before being circulated on the market.

The overall assessment shows that Vietnam has established a relatively comprehensive legal framework to promote energy transition and biofuel development.

Consequently, some achievements in biofuel production in Vietnam can be observed like the construction of a number of biofuel facilities. Nevertheless, this progress seems to slow down since 2015, because only 2 ethanol facilities are still in operation. The legal framework covers many different areas and activities, such as climate change, renewable energy development, decarbonisation of the power system, energy efficiency and the just energy transition. Vietnam already has an important legal foundation to implement the energy transition while facilitating and promoting these activities through continuous improvements to the legal framework. Notably, the policy system and legal regulations related to climate change, green economy, just and equitable transition have been improved. However, further attention is needed to continue to build and strengthen the regulatory framework, especially in areas such as renewable energy development and decarbonisation of the electricity system.

3 Vietnam's energy supply and bioethanol market

3.1 Vietnam's energy supply

In 1986 the Doi Moi economic reforms were introduced. Vietnams service and industrial sector grew rapidly leading to a constant gross domestic product (GDP) growth from 6.47 billion US$ in 1990 to 271.16 billion US$ in 2020.[7] Due to the rapid economic development and other drivers like urbanisation and income growth Vietnam's energy demand increased fast while its power mix changed.

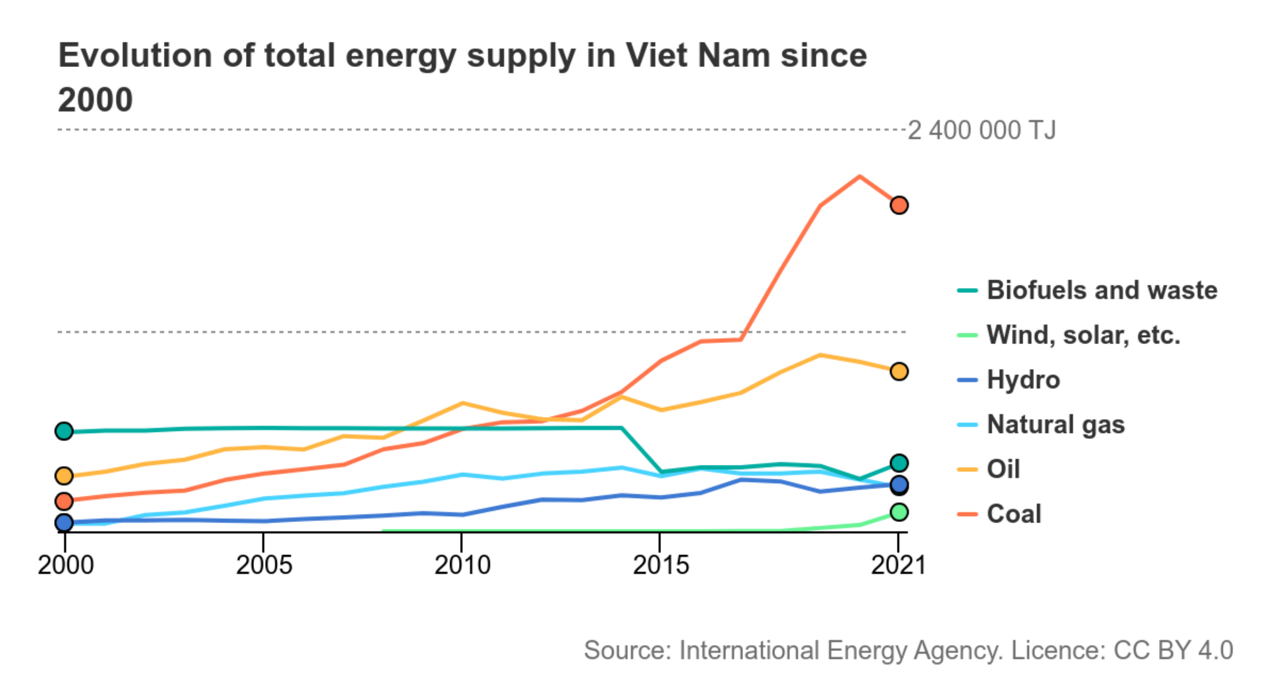

Figure 1: Evolution of total energy supply in Vietnam since 2000 (IEA 2024)

Figure 1 underlines this development by depicting the total energy supply in Vietnam from 2000 to 2021. Nowadays, Vietnam mainly depends on fossil fuels like coal, crude oil and natural gas as energy sources, which accounted for 80 percent of the total energy production in 2021 (Figure 2). Moreover, energy imports accounted for 34 percent of the total energy supply in 2021 emphasizing Vietnams dependency on the international energy market. However, renewable energy sources like solar-, wind- and hydropower as well as biofuels and waste play a more and more important role in Vietnam's energy supply and made up 21 percent in 2021.[8] Consequently, Vietnam already achieved the goal of Resolution No. 55-NQ/TW and the National Strategy on Green Growth to reach about 15-20 percent of renewable energy sources in the total primary energy supply by 2030 (See 2.1). Indeed, Vietnam has a significant potential for further generating electricity from biomass and biogas sources.[9] Even though, around 35 percent of the total energy supply came from biofuels and waste in 2000 it can be assumed that back then especially firewood was used as bioenergy source on the household level resulting in environmental damages like deforestation.

[7] IEA (2024)
[8] IEA (2024)
[9] WWF (2016)

Vietnam has also some support mechanisms for electricity generation from renewable energies like exceptions from duties, tax benefits and feed-in-tariffs. For instance, Vietnam Electricity (EVN) is obliged to buy any electricity generated from renewable energy sources.[10]

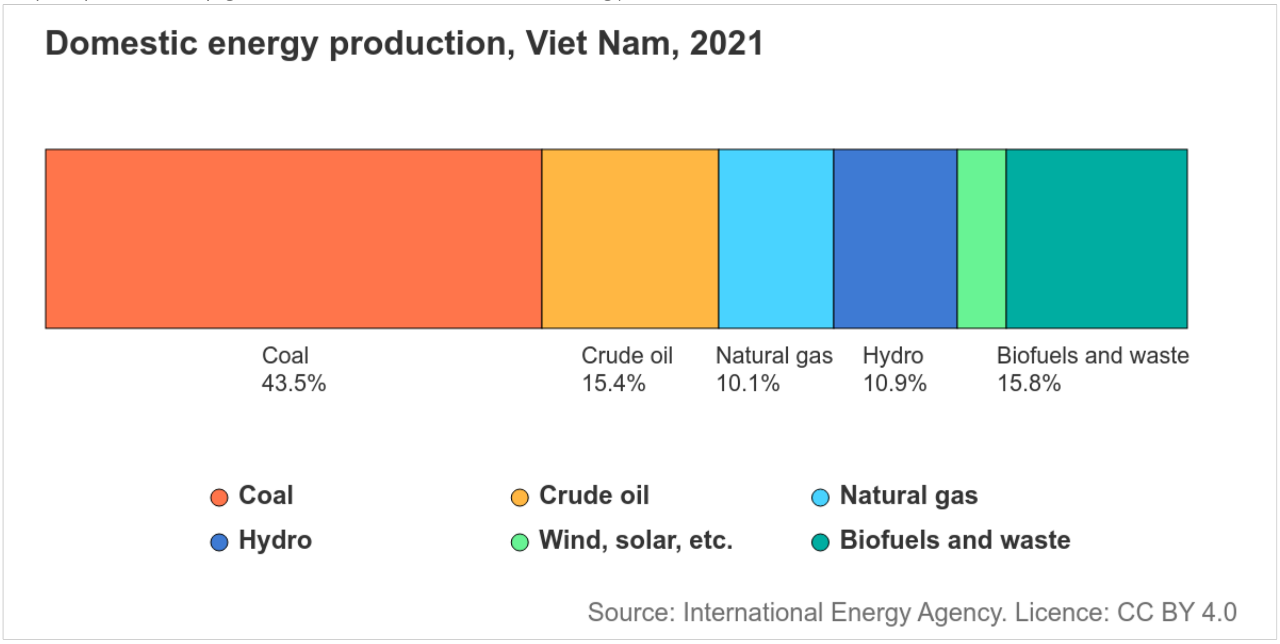

Figure 2: Total energy supply, Vietnam (IEA 2024)

Until 2045 Vietnam wants to reach a share of renewable energy sources of 25-30 percent in the total primary energy supply (see Section 2.1). This further underlines the relevance of the CPEP project in promoting the cultivation of cassava for bioethanol production on post-mining sites as a means to increase the domestic share of renewable energy in the total energy supply in Vietnam.

3.2 Vietnam's bioethanol market

Vietnam faces a continuously rising energy demand while the development of renewable energy is still ongoing (see Section 3.1). As a net importer of transportation fuels, Vietnam is vulnerable to volatilities in global fuel prices. The domestic production of bioethanol might enable Vietnam to reduce its import dependency and to improve its trade balance.[11] Therefore, it is rewarding for the Vietnamese government to invest in alternative energy sources like bioethanol. However, the promotion of renewable energy in Vietnam is slowed down by influential energy enterprises supporting the existing energy system. For example, decision-makers doubt that renewable energy might provide a stable energy supply, because they perceive it as not constantly available.[12] In addition to that, the Vietnamese technology for producing bioethanol is old, lacks behind foreign standards and is thus often not competitive with conventional fossil fuels due to a high energy consumption and low productivity.[13] Promoting technology transfer and persuading decision makers that a well-established bioethanol industry reliably contributes to the country's energy security is crucial. Therefore,

[10] Vieweg et al. (2017)
[11] Trinh and Le (2018)
[12] Neefjes. Koos; Dang Thi Thu Hoai (2017)
[13] World Energy Council (2016)

the cultivation of cassava on post-mining sites might serve as a best-practice example for decision makers to support Vietnam's bioethanol production.

In the 2010s, the bioethanol industry in Vietnam was based on cassava as the only feedstock.[14] The planted area of cassava increased by 5 percent from 498,000 ha in 2010 to 524,500 ha in 2021. At the same time, the cassava yield increased by 17 percent from 19.02 ton/ha to 22.2 ton/ha, whereas the overall cassava production increased from 8,595,600 tons to 10,565,600 tons.[15] In 2019, the country had seven ethanol facilities with a total capacity of 612 million litres per year. However, due to an unstable supply of feedstock only Ethanol Tung Lam in Dong Nai and Bioethanol Dai Tan in Quang Nam operate with a capacity of 72 and 125 million litres (56,808 and 98,750 tons) per year, respectively. Vietnam so far failed to achieve the goal of Decision 177/2007 / QD-TTg to increase the output of ethanol and biodiesel to 1.8 million tons by 2025. The bioethanol plant in Quang Nam province still processes cassava chips but the one in Dong Nai province has switched its feedstock to maize since it is easier to ensure the supply of maize in quantity and quality in Vietnam in comparison to cassava. Moreover, Chinas growing demand for cassava increases the export price in comparison to the domestic purchase price. For example, between 2013 and 2016, just 1 -3 percent of the cassava harvest was used for producing bioethanol in Vietnam, because Vietnamese farmers rather sell their cassava on the Chinese than on the domestic market thereby reducing the domestic supply.[16] Indeed, Vietnams cassava exports increased by 22 percent from 961 Mio USD to 1176 Mio USD between 2018 and 2021.[17] Ethanol facilities additionally compete for cassava with starch and animal feed producers .[18] The increased domestic cassava consumption leads to increasing prices and makes cassava as a feedstock uncompetitive for bioethanol production compared to imported maize.[19] Thus, negotiating cassava offtake contracts between farmers and ethanol manufacturers and offering advice for farmers on how to increase their productivity might ensure a stable supply of feedstock to the ethanol facilities in Vietnam.[20] Otherwise, the bioethanol industry may further rack up losses jeopardizing thousands of jobs and millions of dollars in investment.

Fuel losses due to evaporation as well as transportation and storage costs are higher for E5 than for conventional gasoline. Therefore, many biofuel sellers do not provide consumers with biofuels.[21] Petrolimex and PVOil are the two biggest fuel enterprises in Vietnam and they have different distribution strategies. Petrolimex uses 7 blending stations with an overall capacity of 1.8 billion litres, whereas PVOil uses 12 blending stations with an overall capacity of 1.67 billion litres. Using many small capacity blending stations enables PVOil to respond quickly to the rising demand for E5 and to reduce losses and transportations costs.

In 2017, Decision No. 255/TB-VPCP was announced by the Vietnamese Government. It obliges gasoline traders to replace conventional gasoline like RON 92 with E5 nationwide since the beginning of 2018[22]. As a result, Decision No. 255/TB-VPCP influenced the share of E5 in the total gasoline consumption to increase from 9 percent in 2017 to 32 percent in 2020.[23]

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14 UfU (2018b)
15 General Statistics Office (2023)
16 Nghiem et al. (2021)
17 General Statistics Office (2023)
18 Trinh and Le (2018)
19 USDA (2020)
20 Nghiem et al. (2021)
21 Trinh and Le (2018)
22 Vietnam Government Office (2017)
23 Nghiem et al. (2021)

The Vietnamese Government wants to incentivize consumers to buy E5 gasoline through the excise tax, environmental protection tax and stabilisation fund. Nevertheless, the current price difference between E5 and RON95 of around VND 1,400 to 1,600 per litre is not sufficient for consumers to prefer the former over the latter.[24] Indeed, the Environmental Protection Tax applied on E5 is just 5 percent lower than on RON95.[25] If the Vietnamese government wants consumers to prefer E5 gasoline, it consequently needs to increase the price differences for example through import tariffs and CO_2 taxes on fossil fuels.[26] Some experts suggest the price gap to be at least VND 2,000 to make E5 more attractive to Vietnamese consumers than RON95.[27] However, many consumers are afraid that E5 gasoline might damage their engines and are also not aware about the environmental benefits of biofuels.[28] The Vietnamese government thus has to improve consumers awareness on the good quality of biofuels for example through PR campaigns.
Lastly, Vietnam imports bioethanol from the United States and South Korea to supplement the local production and demand. The country even reduced the MFN (most-favoured-nation) import tariffs for bioethanol to 15 percent in 2020.[29] However, reducing import tariffs further promotes the import of bioethanol and might reduce the domestic production, if the domestic prices cannot compete.

[24] Nghiem et al. (2021)
[25] USDA (2020)
[26] Nghiem et al. (2021)
[27] USDA (2020)
[28] Trinh and Le (2018)
[29] USDA (2020)

4 Cassava production on the test-site in Lam Dong Province

4.1 Key data of the test site in Lam Dong Province

The test site is situated in the Central Highlands of Southern Vietnam, 160 km northeast of Ho Chi Minh City in Bao Lam District in the Lam Dong Province. The plantation has a total size of 2 ha and is on the area of the Tan Rai bauxite mine managed by VINACOMIN. The precipitation data classifies the Bao Lam district as Tropical Monsoon Climate (Am) according to the Köppen-Geiger system with an average annual temperature of 23 °C and an average annual precipitation of 3,370 mm. With a maximum of about 29.4 °C, April is the warmest month. January has the lowest minimum temperature at about 15.8 °C. The driest month is February with 77 mm of precipitation. August is the month with the highest precipitation at about 586 mm. Before the mining activities began, the topsoil was extracted and stored. After mining ceased, the previously removed topsoil was reapplied. Due to this procedure, the original soil structure was destroyed. The original soil type in this area is a Xanthic Ferrasol, a silty clayey sand on basalt stone with a reddish to yellow-brown colour. 1.6 ha of the total plantation area of 2 ha were used for cassava cultivation and the remaining 0.4 ha for the cultivation of V06 grass. Cassava and VA06 grass were selected, because they seemed to be well adapted to the local conditions. Depending on availability, the KM94 or KM140 cassava varieties preferred for bioethanol production are planted from cuttings at intervals of 80 cm x 80 cm or 100 cm x 80 cm (depending on soil quality) in shallow ridges. Even though KM140 has a low starch retention time, it brings multiple advantages like wide adaptability to different ecological conditions, little breakage, fast soil cover as well as high resistance to pests and diseases. Mung beans are used as an intercrop to accelerate ground cover.

4.2 Cassava harvest and yield at the test site in Lam Dong Province

Cassava was harvested nine months after planting on January 15th and 16th 2022. The survival rate was 90 percent due to one area with less growth. The actual quantity of cassava was smaller than expected, because 20-30 percent of the cassava plants were stolen right before harvest, even though the testing site was fenced and locked. The stolen plants were not removed from a specific area, but from individual plants over the entire area. Thus, the theft was not immediately evident and only detectable by our experts. It was detected on 14th of January 2022 on the day of sampling for the soil and biomass analysis. It can be assumed that the plants with the highest growth and root yield were stolen. Moreover, it was very difficult to uproot cassava due to the hard soil and improper harvesting methods causing cassava roots to be broken and left in the soil.

Table 2: Properties of the cassava plants harvested January 2022 (n=10/subplot, 160 in total)

	Stem height	Whole plant weight	Cassava roots fresh matter	Cassava roots fresh matter yield
Subplots	(cm)	(kg per plant)	(kg per plant)	(t per ha)
1	65.90	0.95	0.55	7.09

2	66.70	1.11	0.63	8.19
3	67.70	1.32	0.76	9.82
4	70.70	1.31	0.63	8.13
5	65.70	1.35	0.74	9.56
6	61.10	0.94	0.53	6.89
7	68.30	1.68	0.88	11.38
8	54.80	0.92	0.47	6.11
9	66.20	1.15	0.58	7.54
10	61.80	0.61	0.37	4.81
11	74.90	1.21	0.58	7.54
12	65.40	0.84	0.49	6.38
13	74.30	1.33	0.80	10.40
14	61.70	1.01	0.65	8.45
15	71.60	1.50	0.89	11.57
16	76.50	1.18	0.71	9.17
Arithmetic mean	67.08	1.15	0.64	8.31
Median	66.45	1.16	0.63	8.16

The stem height is smaller than on other conventional cultivation areas. Considering the flat area without elements in the surroundings to protect against wind, the mean stem height of 67.08 cm is to be evaluated as an adaptation to the strong winds and protection against wind-breakage. In addition to that, 2.5-months after planting, the weather was hot, dry and sunny thereby affecting the growth and height of the plants. Low plants and small foliage reduce the photosynthetic productivity of the cassava plants and thus lead to low yields. Furthermore, the cassava plants were grown on newly restored and fragmented soils with less nutrients than in conventional soils. The mean cassava root yield of all 16 plots is 8.31 t/ha (see Table 2). However, subplots 6, 8, 10 and 12 in which part of the subplot showed almost complete failures, are of great influence. If one neglects the yields of subplots 6, 8, 10 and 12 and only considers the remaining ones the mean value of the remaining subplots is 9.07 t/ha. In comparison with the cassava root yield of 19 t/ha produced on average in the Bao Lam district in 2020[30] (see Table 3) this is about 44 and 48 percent, respectively. Moreover, it should be remembered that 30 percent of the plant was stolen before harvest. It is likely that the best-grown and highest-yielding individual plants were stolen from the field. This is also a crucial fact that has to be taken into account in the yield discussion, but which we cannot compensate for mathematically.

Table 3: Average cassava yields in Lam Dong 2016-2020

Districts	2016	2017	2018	2019	2020
Đam Rong	19.97	21.00	21.00	21.05	21.77
Lac Duong	8.00	8.00	8.00	8.10	16.50
Lam Ha	12.84	12.42	12.40	12.50	20.33
Duc Trong	20.00	20.00	20.00	20.00	18.60
Bao Lam	8.50	8.55	8.77	19.22	19.00
Da Huoai	10.62	10.75	10.76	11.31	18.50
Da Teh	21.50	21.61	21.50	21.47	21.55

[30] General Statistics Office (2022)

Cat Tien	17.30	17.25	17.30	17.30	17.40
Average	**19.99**	**19.83**	**19.19**	**20.00**	**20.75**

Table 4 shows selected ingredients of the dried cassava tubers cultivated on the test-site in Lam Dong Province. A high starch content is especially important for the efficient processing of dried cassava chips into bioethanol. The average starch content of the dried cassava chips cultivated on the test-site is 72 percent. In the literature, the average starch content is slightly lower (67 percent)[31] or around the same (67-75 percent)[32]. This shows that cassava cultivated on the test-site in Lam Dong can compete with conventional production and is well suited for being processed into bioethanol.

Table 4: Selected ingredients of the cassava tubers.

Dry matter content	Starch	Sugar	Fibre	Ash	Protein	Lipid
Subplots	%	%	%	%	%	%
1	81,9	91,0	1,2	2,4	6,8	1,6
2	72,9	81,0	1,6	2,5	6,3	0,9
3	53,1	59,0	1,3	2,7	6,8	1,4
4	64,8	72,0	1,2	2,5	6,8	1,3
5	72,9	81,0	1,9	2,7	6,4	1,0
6	67,9	75,0	1,8	2,6	6,5	1,1
7	69,8	77,0	1,9	2,3	6,6	2,7
8	57,2	63,5	1,9	2,2	6,8	1,8
9	76,9	85,5	1,9	2,4	6,3	1,8

[31] Fanelli et al. (2023)
[32] Pornpraipech et al. (2017)

10	81,9	91,0	1,9	2,1	7,0	2,2
11	80,1	89,0	1,1	2,2	7,1	1,1
12	79,2	88,0	1,5	2,4	6,3	1,3
13	74,7	83,0	1,2	2,5	6,7	3,0
14	71,6	79,5	1,2	2,5	6,8	1,9
15	72,9	81,0	1,2	2,6	7,1	1,5
16	74,7	83,0	1,2	2,5	7,1	1,7
Arithmetic mean	**72,0**	**80,0**	**1,5**	**2,5**	**6,7**	**1,6**
Median	**72,9**	**81,0**	**1,4**	**2,5**	**6,8**	**1,5**

5 Potential for saving greenhouse gas emissions

A life cycle analysis (LCA) approach was chosen to assess the potential greenhouse gas (GHG) savings from bioethanol produced from cassava cultivated on post-mining sites. The stages of the production chain include land use change; cassava cultivation; chipping; feedstock production; transformation and delivery to the ethanol plant; biomass processing into biofuels; and biofuel transportation, storage, and distribution (Figure 3). Thereby, it is possible to identify how the different steps of the production chain contribute to the total GHG emissions. Lastly, the GHG emissions of bioethanol are compared to the ones of gasoline to assess the potential savings. Three different GHGs are considered: CO_2, CH_4, and N_2O. They are aggregated to the CO_2 equivalent (CO_{2eq}) by using the Global Warming Potential (GWP) factors:

$GWP_{CO2\ fossil} = 1$; $GWP_{CO2\ biogenic} = 1$; $GWP_{CH4\ fossil} = 25$; $GWP_{CH4\ biogenic} = 25$; and $GWP_{N2O} = 298$.[33]

The GHG emissions from ethanol production are calculated using the guidelines from Bio-Grace and the European Commission[34]:

Data from the process *(e.g. yields, fertiliser)* x Data for conversion *(e.g. heating values, emission factors)* = GHG emissions *(incl. direct and indirect emissions)*

Because 30 percent of the cassava plants were stolen from the test site in Lam Dong province before the harvest and the yields of the 16 subplots vary greatly, 2 different scenarios are evaluated in the LCA.

Scenario 1: yield’s mean value of all plots in Lam Dong = 8.42 t/ha

Scenario 2: 0,75-quantile of all plots in Lam Dong (upper 25 percent of the values) = 11.7 t/ha

[33] Greenhouse Gas Protocol (2024)
[34] Biograce (2024)

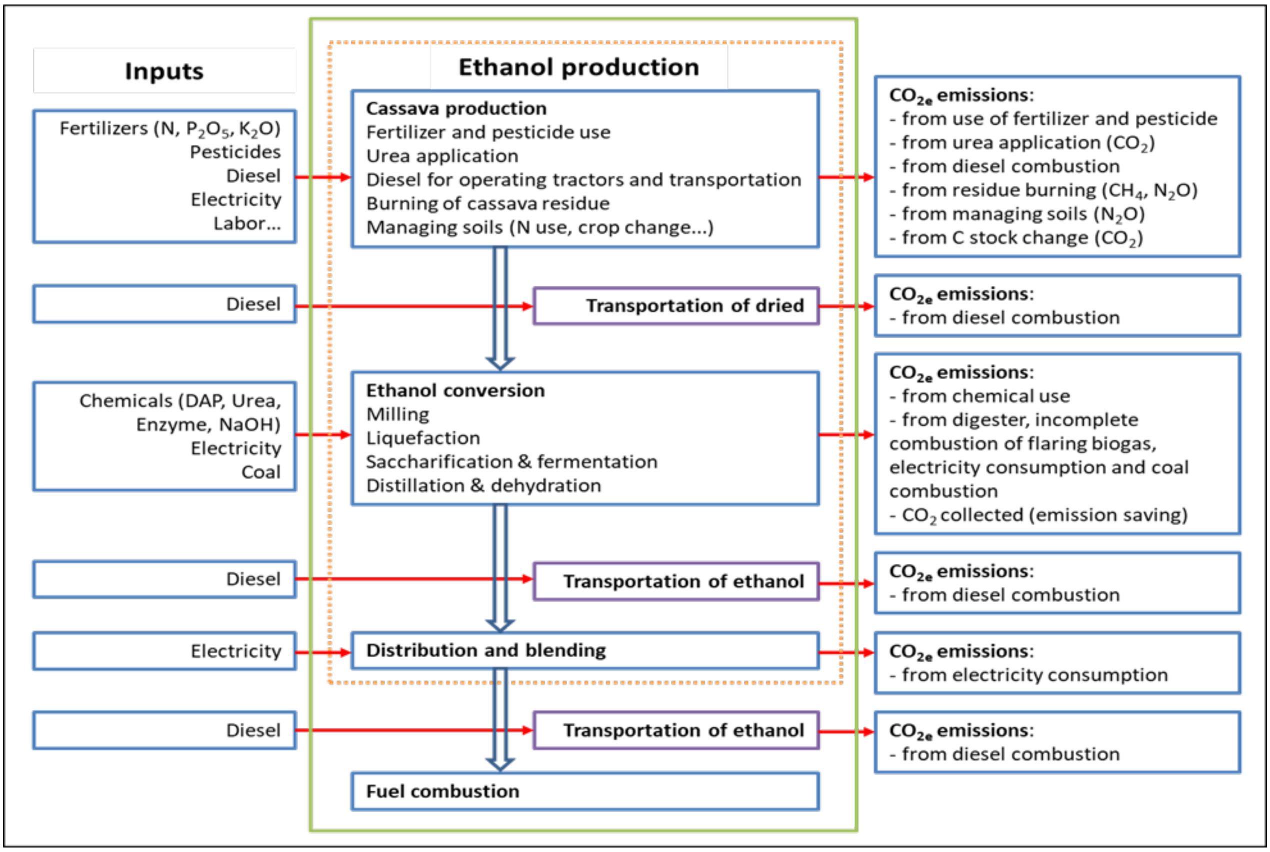

Figure 3: LCA stages of ethanol production and utilization

5.1 GHG mitigation potential of Scenario 1

Scenario 1 is used to calculate the GHG emissions savings potential of the actual harvest. Scenario 2 is used as comparison to demonstrate how the GHG emissions savings potential could be if no plants have been stolen. Both scenarios include the cultivation of cassava on the test site in Lam Dong province, the use of cassava as ethanol production's material and the use of ethanol for E5 gasoline blending in the South of Vietnam.

To evaluate the cassava based ethanol pathway of Scenario 1 and 2 the following inputs need to be considered. During the growing process no pesticides have been used and the cassava planting density was 13,000 plants/ha. Per ha 5 tons of chicken compost, 1 ton of Nong Hai compost, superphosphate: 500 kg, urea: 350 kg, potassium: 400 kg and 300 kg NPK (16:16:16) have been used as fertilizer.[35]

After being harvested, cassava is manually sliced and dried in the sun before being delivered to ethanol plants as dried chips. The final water content is on average about 14 percent and the conversion ratio of fresh root to dried chips is about 2.5 kg/kg. The dry cassava chips are transported from the test site to the plants by 40 t truck, whose diesel consumption is on average 0.28 L/km. Currently, in Vietnam only two bioethanol plants from Tung Lam company are under operation. The bioethanol plant in Quang Nam province still uses cassava

[35] UfU (2023)

chips as feedstock and is considered in the LCA for producing bioethanol from cassava cultivated on the test site in Lam Dong province. The second bioethanol plant in Dong Nai province nowadays uses maize as feedstock, because it is easier to ensure a sufficient supply in quantity and quality in comparison to cassava. It is for this reason that the bioethanol plant in Dong Nai province is not considered in the LCA. Arriving at the bioethanol plant the dried cassava chips are converted to ethanol through four steps namely milling, liquefaction, saccharification and fermentation as well as distillation and dehydration. As by-products dried distiller's grains are sold for animal feed production, biogas is used as a supplemental energy, and liquid CO_2 is collected for sale to fire protection facilities or beverage plants, where it is loaded into fire extinguishers or beverage bottles, respectively. The latter is not considered in the LCA because the data on electricity used for CO_2 liquidation is not available. However, the collected CO_2 still causes GHG impact indirectly. The bioethanol is then sold to oil companies and delivered to blending stations by 30 m^3 trucks with an average diesel consumption of 0.28 l/km. Most of the petroleum distribution companies use the "in-line blend" method, in which gasoline and ethanol are blended directly in line before being transferred by truck and ship to the gasoline station. There are several blending systems installed so far across the country. [36] All input data are listed in detail in Table 5. The precise results of scenarios 1 and 2 are depicted in Table 6 and Table 8, respectively.

Table 5: LCA input data for cassava-based ethanol production in Vietnam

	Scenario (1) and (2)	Functional Unit
Land use change		
Land use change (aLUC)	-0.02	kg CO_2eq / ha*a
Cultivation		
Yield		
Cassava	8.42, 11.7	t/ha*a
Water content	59.8	%
harvest residue	55.1	t/ha*a
Fertilizer & pesticides		
Urea	161.0	kg N / ha*a
manure	82.5	kg N / ha*a
P2O5-Fertilizer	150.0	kg P_2O_5 / ha*a
K2O-Fertilizer	220.0	kg K_2O / ha*a
CaO-Fertilizer (kg CaCO3)	5.4	kg $CaCO_3$ / ha*a
Pesticides	0	kg / ha*a
Seeds		

[36] Nguyen et al. (2018)

Cassava cuttings	8,750	kg / ha*a
Energy		
Diesel	22.5	L / ha*a
Electricity using (for irrigation)	45.0	kWh / ha*a
Electricity mix	Electricity mix Vietnam	
Transport of cassava roots		
Distance	10.0	km
Transport vehicle	Truck (40 t) for dry products	
Fuel	Diesel	
Chipping (pieces by hand)		
Yield	0.400	kg chips / kg cassava
Transport of cassava chips		
Distance	596.0	km
Transport vehicle	Truck (40 t) for dry products	
Fuel	Diesel	
Processing - ethanol plant		
Ethanol	0.348	kg ethanol/kg cassava chips
Co-products		
Stillage cake	0.361	kg / kg cassava chips
Water content	20.0%	%
CO2		kg / kg ethanol
Chemicals		
Alpha-amylase	0.00025	kg / kg ethanol
Gluco-amylase	0.000765	kg / kg ethanol
Urea	0.0047	kg / kg ethanol
Electricity consumption	0.274	kWh / kg ethanol
Electricity mix	Electricity mix Vietnam	
heat consumption	12.72	MJ / kg ethanol

covered by biogas CHP	40%	%
covered by hard coal CHP	60%	%
covered by wood chips CHP	0%	
Energy from biogas CHP		
efficiency of heat production	90%	%
Biogas from wastewater		MJ / kg ethanol
Energy from coal-CHP		
efficiency of heat production	90%	%
hard coal	8.48	MJ / kg ethanol
Energy from wood-CHP		
efficiency of heat production	90%	%
wood chips	2.12	MJ / kg ethanol
Allocation over main- and co-product		
Ethanol	1.0	MJ
Stillage cake	0.507	MJ/MJ Ethanol
Heating value products sum	1.507	MJ
Emissions allocated to ethanol	66.4%	%
Transport		
Distance	254.7	km
Transport vehicle	Truck (40 t) for liquids	
Fuel	Diesel	
Filling station		
Electricity consumption	0.0050	kWh / kg ethanol
Electricity mix	Electricity mix Vietnam	

The LCA shows in general that most GHG emissions come from cassava cultivation and burning solid fuels for steam production during the ethanol conversion. However, it can be assumed that the GHG emissions caused by field burning after the harvest is balanced out by carbon sequestration during the cultivation.[37] Moreover, the GHG emissions during the ethanol conversion are partly balanced out by the amounts of biogas used for Combined Heat and Power (CHP) generation and the allocation for dry stillage. In Scenario 1 the cassava yield's mean value of 8.42 t/ha is taken into account in the LCA (Table 6).

[37] Le et al. (2013)

Table 6 LCA GHG emissions from cassava-based ethanol production in Scenario 1

	Greenhouse gases					
	g CO_2 fossil	g CO2 biogenic	g CH_4 fossil	g CH4 biogenic	g N_2O	**g CO_{2eq}**
Land use change *(sum per ha)*		-16	-	-	-	-16
Land use change (aLUC)		-16				-16
Cultivation *(sum per ha)*	1221994	0	2200	336.232	5215	2839326
Fertilizer & pesticides						
Urea	274120	0	1495	0	0	**311500**
P2O5-Fertilizer	169276	0	314	0	5.07	**178636**
K2O-Fertilizer	127475	0	241.8	0	2.908	**134386**
CaO-Fertilizer (kg CaCO3)	227	0	0.5	0	0.008	**242**
N2O field emissions - mineral fertilizer					3352	**998971**
N2O field emissions - organic fertilizer					1847	**550528**
Emissions from field burning of residues				336	3.3	**9391**
Seeds						
Cassava cuttings	559176	0	0.000	0	0.000	**559176**
Energy						
Diesel	68715	0	107	0	0.42	**71509**
Emissions from diesel usage (agriculture)			1.03		2.5	**784**
Electricity consumption (for irrigation)	23004	0	40.338	0	0.638	**24203**
Transport of cassava roots *(sum per kg cassava)*	0.69	0	0.00111	0	0.000019	0.72
Diesel	0.69	0	0.00111	0	0.000019	**0.72**
Chipping *(pieces by hand)*						
Diesel	0	0	0	0	0	**0.00**
Transport of cassava chips *(sum per kg chips)*	41.17	0	0.06595	0	0.001148	43.16
Diesel	41.17	0	0.06595	0	0.001148	**43.16**

Processing - ethanol plant *(sum per kg ethanol)*	1027	0	5.96	1	0.0369	1218
Chemicals						
Alpha-amylase	5.7	0	0.0082	0	0	**0.26**
Gluco-amylase	8.0	0	0.0436	0	0	**5.91**
Urea	8.0	0	0.0436	0	0	**9.09**
Emissions from energy consumption						
Electricity mix	140	0	0.246	0	0.004	**147.37**
Emissions from biogas-CHP	0	0	0	1.05	0.009	**28.83**
Biogas from wastewater	5.1	0	0.01	0	0.001	**10.74**
Coal-CHP	0	0	0.008	0	0.017	**5.28**
Hard coal	868	0	5.64	0	0.006	**1011**
Allocated emissions *(sum per kg ethanol)*	1460	0	5.33	0.7651	2.97	2498
Cumulated emissions per kg ethanol	2201	0	8.03	1.1530	4.48	**3765**
Cumulated allocated emissions per kg ethanol	1460	0	5.33	0.7651	2.97	**2498**
Transport ethanol via blending to filling station	21.5	0	0.0349	0	0.00060	22.57
Transport						
Diesel	18.9	0	0.0304	0	0.000528	**19.86**
Filling station						
Electricity consumption	2.6	0	0.0045	0	0.000071	**2.71**
Fuel use *(sum per MJ ethanol)*	0	0	0.0008	0	0.00320	0.97
Emissions from Ethanol usage	0	0	0.0008	0	0.00320	**0.97**

The total GHG emissions of the cassava-based ethanol are 94.41 g CO_{2eq}/MJ ethanol, of which 63 percent and 32 percent of the contribution come from the cassava cultivation and ethanol processing, respectively (Table 7, Figure 4).

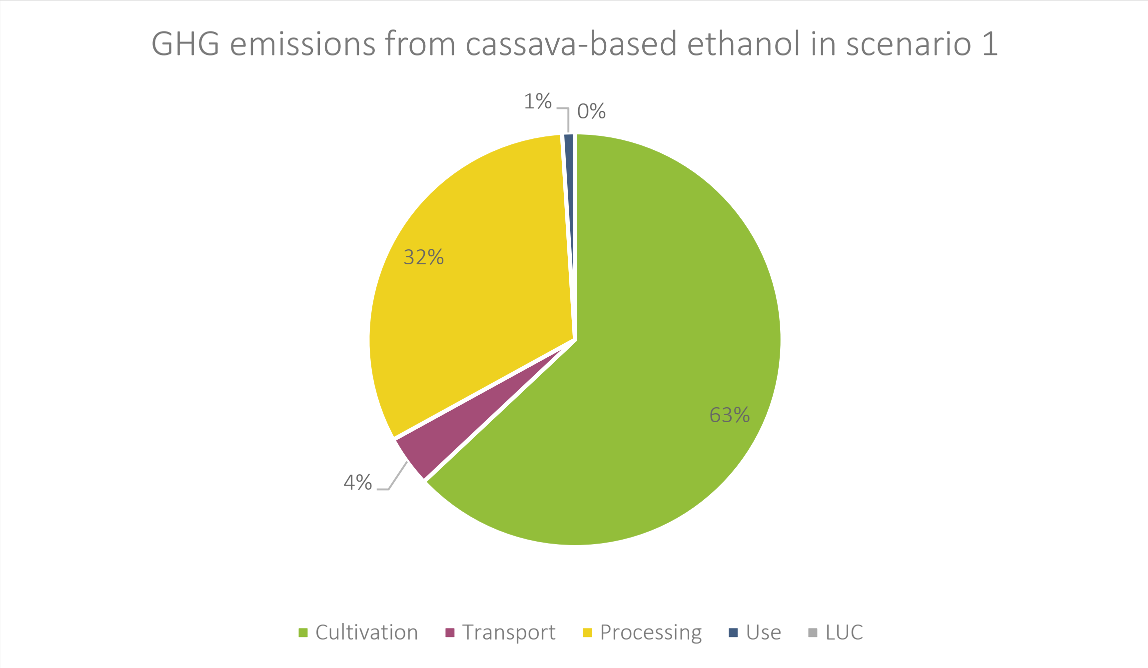

Figure 4: GHG emissions from cassava-based ethanol in Scenario 1

The average yield of 8.4 t tubers/ha is relatively low compared to the agricultural average of 19.0 t of tubers/ha of cassava for the Bao Lam District. However, it is already sufficient to result in GHG emissions equivalent to those of gasoline (94.0 g CO2eq/MJ petrol). Moreover, the total GHG emissions from vehicles using the blended product as E5-biofuel are 235.04 g CO2eq/km compared to 241.03 g CO2eq/km for gasoline. The use of E5 blended with cassava-based ethanol thus saves 2.48 percent GHG emissions in comparison with gasoline (See Table 7). That's probably because the fuel efficiency, heat consumptions per kilometer, of biofuels like E5 are higher than the one of gasoline. Nevertheless, it should be considered that fuel efficiency is also affected by other factors such as vehicle speed and gear, vehicle models, and road conditions.[38]

Table 7: GHG emissions balance: comparison between biofuel and gasoline in Scenario 1

	Ethanol from	Fossil petrol	Saving	E5-biofuel	Fossil petrol	Saving
	cassava	(gasoline)		(cassava-based)	(gasoline)	
	G CO_{2eq}/MJ EtOH	g CO_{2eq}/MJ petrol	%	g CO_{2eq}/km E5-use	g CO_{2eq}/km petrol-use	%
LUC	-0.00033					
Cultivation	59.71943					
Transport	3.56417					
Processing	30.15258					

[38] Le et al. (2013)

Use	0.97329					
Total	94.41	94.0		235.04	241.03	2.48%

5.2 GHG mitigation potential of Scenario 2

In Scenario 2 the 0,75-quantile of the cassava yield 11.7 t/ha is taken into account in the LCA (see Table 8).

Table 8: LCA GHG emissions from cassava-based ethanol production in Scenario 2

	Greenhouse gases					
	g CO_2 fossil	g CO2 biogenic	g CH_4 fossil	g CH4 biogenic	g N_2O	**g CO_{2eq}**
Land use change *(sum per ha)*		-16	-	-	-	-16
Land use change (aLUC)		-16				-16
Cultivation *(sum per ha)*	1221994	0	2200	336.232	5215	2839326
Fertilizer & pesticides						
Urea	274120	0	1495	0	0	**311500**
P2O5-Fertilizer	169276	0	314	0	5.07	**178636**
K2O-Fertilizer	127475	0	241.8	0	2.908	**134386**
CaO-Fertilizer (kg CaCO3)	227	0	0.5	0	0.008	**242**
N2O field emissions - mineral fertilizer					3352	**998971**
N2O field emissions - organic fertilizer					1847	**550528**
Emissions from field burning of residues				336	3.3	**9391**
Seeds						
Cassava cuttings	559176	0	0	0	0	**559176**
Energy						
Diesel	68715	0	107	0	0.42	**71509**
Emissions from diesel usage (agriculture)			1.03		2.5	**784**
Electricity consumption (for irrigation)	23004	0	40.338	0	0.638	**24203**
Transport of cassava roots *(sum per kg cassava)*	0.69	0	0.00111	0	0.000019	**0.72**
Diesel	0.69	0	0.00111	0	0.000019	**0.72**

Chipping *(pieces by hand)*						
Diesel	0	0	0	0	0	**0.00**
Transport of cassava chips *(sum per kg chips)*	41.17	0	0.06595	0	0.001148	43.16
Diesel	41.17	0	0.06595	0	0.001148	**43.16**
Processing - ethanol plant *(sum per kg ethanol)*	1027	0	5.96	1	0.0369	1218
Chemicals						
Alpha-amylase	5.7	0	0.0082	0	0	**0.26**
Gluco-amylase	8.0	0	0.0436	0	0	**5.91**
Urea	8.0	0	0.0436	0	0	**9.09**
Emissions from energy consumption						
Electricity mix	140	0	0.246	0	0.004	**147.37**
Emissions from biogas-CHP	0	0	0	1.05	0.009	**28.83**
Biogas from wastewater	5.1	0	0.01	0	0.001	**10.74**
Coal-CHP	0	0	0.008	0	0.017	**5.28**
Hard coal	868	0	5.64	0	0.006	**1011**
Allocated emissions *(sum per kg ethanol)*	1266	0	4.98	0.7117	2.14	2048
Cumulated emissions per kg ethanol	1908	0	7.50	1.0726	3.23	**3086**
Cumulated allocated emissions per kg ethanol	1266	0	4.98	0.7117	2.14	**2048**
Transport ethanol via blending to filling station	21.5	0	0.0349	0	0.00060	22.57
Transport						
Diesel	18.9	0	0.0304	0	0.000528	**19.86**
Filling station						
Electricity consumption	2.6	0	0.0045	0	0.000071	**2.71**
Fuel use *(sum per MJ ethanol)*	0	0	0.0008	0	0.00320	0.97
Emissions from Ethanol usage	0	0	0.0008	0	0.00320	**0.97**

The total GHG emissions of the cassava-based ethanol are 77.67 g CO2eq/MJ ethanol, of which 55 percent and 39 percent of the contribution come from the cassava cultivation and ethanol processing, respectively (Table 9, Figure 5).

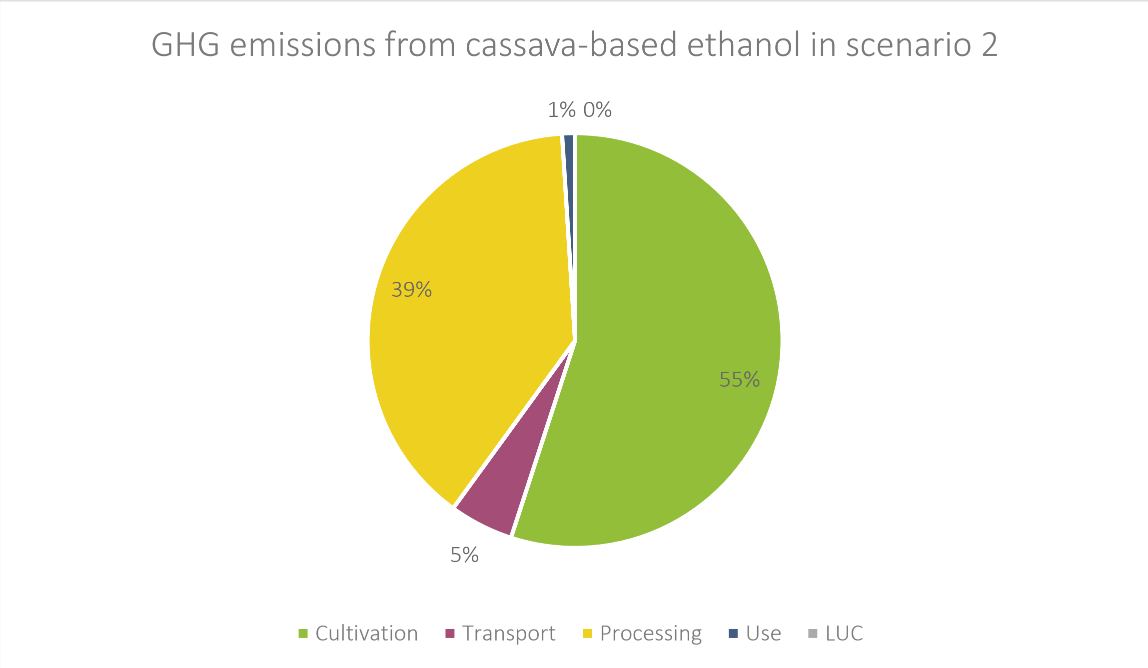

Figure 5: GHG emissions from cassava-based ethanol in Scenario 2

In Scenario 2 the total GHG emissions of producing cassava-based ethanol are 17.38 percent less than the ones from gasoline (94 g CO2eq/MJ petrol). So, the mean yield of 11.7 t/ha of cassava is sufficient to result in GHG emissions savings throughout the production process. Moreover, the total GHG emissions from vehicles using the blended product as E5-biofuel are 232.96 g CO2eq/km compared to 241.03 g CO2eq/km for gasoline. The use of E5 blended with cassava-based ethanol thus saves 3.35 percent GHG emissions in comparison with gasoline (Table 9).

Table 9: GHG emissions balance: comparison between biofuel and gasoline in Scenario 2

	Ethanol from	Fossil petrol	Saving	E5-biofuel	Fossil petrol	Saving
	cassava	(gasoline)		(cassava-based)	(gasoline)	
	g CO_{2eq}/MJ EtOH	g CO_{2eq}/MJ petrol	%	g CO_{2eq}/km E5-use	g CO_{2eq}/km petrol-use	%
LUC	-0.00024					
Cultivation	42.97757					
Transport	3.56417					
Processing	30.15258					

Use	0.97329					
Total	77.67	94.0	17.38%	232.96	241.03	3.35%

The LCA shows that the production and use of bioethanol produced from cassava cultivated on post-mining sites results in less GHG emissions than the production and use of gasoline. In this process, the GHG emissions mainly come from the cassava cultivation and the ethanol processing. So, the potential to reduce GHG emissions at these two stages is still large. Regarding the cassava cultivation, the amount of fertilizers used per ha is quite high in comparison to the yield leading to a large amount of GHG emissions per kg of cassava. So, if the yield per ha is improved, the GHG emissions per kg cassava would be reduced. Avoiding pesticides is an advantage for the environment but negatively affects the cassava yield due to pests and disease.
Regarding the ethanol production, the cassava wastewater discharged from the ethanol factory could be used to recover biogas for steam production. The steam, in turn, can be used directly in the ethanol factory for generating electricity for the ethanol production. There is a need for investing in advanced technologies to improve the efficiency of biogas recovery to reduce the GHG emissions during the ethanol production.

6 Outlook for cassava production on post-mining sites

According to mechanical engineering experts from Hanoi University of Science and Technology and a scientific article on effects of bioenergy on engines and systems,[39] the percentage of ethanol (5 percent) in biofuels additionally improves the engine's working process, enhances economic and technical features, and reduces toxic emissions. There would be even more benefits and GHG emission savings if E10 bioethanol was produced in Vietnam.

Comparing Scenario 1 and 2 with each other raises the assumption that the potential of saving GHG emissions through the production of cassava-based ethanol in comparison to gasoline increases with the yield. Moreover, the cassava yields of Scenarios 1 (8.42 t/ha) and 2 (11.9 t/ha) are much less than on the test site in Thai Ngyuen province during the CPEP 1 project (17.5 t/ha), when bioethanol production from cassava cultivated on former mining sites and its use resulted in 49 percent of GHG emission savings in comparison to the use of gasoline.[40] From this perspective, there is potential to increase GHG savings from the production of cassava-based ethanol on post-mining sites if the yields can be improved in the future. One opportunity would be to use pesticides during cultivation, because the CPEP project completely avoided them. So, the project could try to find the minimum amount of pesticides necessary to improve yields without causing more environmental damages and GHG emissions than in the latest cultivation.

The upscaling of producing bioethanol from cassava is currently also inhibited by the small number of bioethanol plants operating in Vietnam. Only the bioethanol plant of Tung Lam in Quang Nam province still processes cassava chips but the one in Dong Nai province has switched its input to maize, because it is currently easier to ensure the supply of maize in quantity and quality in comparison to cassava in Vietnam. Therefore, growing maize instead of cassava on post-mining sites in future projects is an opportunity if the supply of cassava to the bioethanol plants is still inhibited by high export prices. Nevertheless, maize is susceptible to droughts and cooler temperatures. For this reason, maize was not chosen as a potential energy crop for cultivation on post-mining sites in the CPEP 1 project. In addition, the total GHG emissions from transporting cassava chips to the bioethanol plants would be less if the distance between the cultivation area and the ethanol plant was smaller, thus, if there were more ethanol plants in operation for example in the northern part of Vietnam.

6.1 Co-benefits

Besides climate protection through GHG emissions savings the cultivation of cassava on former mining sites for producing bioethanol brings several co-benefits. Probably most important is the improvement of soil quality, which can support the economic or ecological reuse of the land in the medium term[41] for example for agricultural production or forestry. In this way, recultivating former mining sites offers economic benefits for mining companies thereby encouraging them to do it efficiently.

In the CPEP project, the use of black beans to intercrop the cassava rows effectively reduces soil erosion compared to the 'traditional' approach to reclamation, which involved planting acacia and conifer trees in single rows without ground cover. Moreover, the soil on the test site is more porous and structured after

[39] Le et al. (2013)
[40] UfU (2023)
[41] Brömme et al. (2018)

harvesting cassava than before planting. The literature also suggests that reducing the risk of erosion is a major synergy of planting energy crops on marginal land.[42] From the perspective of soil ecosystem services, the reduction of soil erosion brings benefits on carbon sequestration as soil organic carbon is retained on-site, on flood regulation as the soil organic carbon increases the soil water holding capacity, on agricultural production as soil organic carbon improves soil fertility through better nutrient cycling and storage[43], on climate regulation as GHGs like CO_2 are taken up by the plants and on water purification as especially the soil organic carbon effectively retains contaminants from the seepage water.[44]
Another crucial co-benefit is that the cassava is cultivated on marginal lands, which are not suitable for food production for example due to heavy metal contamination and poor soil quality. So, cultivating cassava for bioethanol production on post-mining sites does not compete with food production and is thereby no threat for food security. In addition to that, the prevention of indirect land use changes (LUC) is a further co-benefit. The conversion of farmland for food production into land for biomass production usually promotes indirect LUC, when the previous food production is relocated into other areas like natural vegetation. Thereby, indirect LUC threatens the environment including biodiversity, soils and climate. However, the cultivation of cassava for bioethanol production on post-mining sites prevents indirect LUC, because it does not compete with food production and does not drive it to natural areas.
In summary, recultivating former mining sites through cassava cultivation brings several economic and ecological co-benefits. Therefore, it is important to further evaluate the potential of scaling up the cassava cultivation on marginal lands in Vietnam.

6.2 Scaling-up potential

As part of the CPEP 2 project, the German engineering office MSP GmbH conducted an analysis of the catchment area of two bioethanol plants operated by Tung Lam in the provinces of Dong Nai and Da Nang. This analysis entailed the recording, evaluation and assessment of marginal areas that could be used for energy crop cultivation, with a view to determine their potential availability. The objective was to identify areas that are not suitable for conventional agriculture. Such areas are typically referred to as 'marginal land' due to site conditions that are unsuitable for highly productive agriculture, including factors such as dryness, steepness, rockiness, salinity, alkalinity, and rocky or saline soil. A total of 1,180 marginal sites were identified in the study area, of which 800 were ultimately identified as potentially suitable for energy crop cultivation, bringing the total area of potential marginal sites in the study area to 22,185 ha. So, what are the potential GHG emissions savings if the potential marginal sites would be cultivated with cassava?
In Scenario 2 of the LCA the fresh root cassava yield on the test-site in Lam Dong Province was 11.7 t/ha or 11,700 kg/ha. The conversion ratio from fresh roots to dried chips is 2.5 kg/kg resulting in 4680 kg/ha dried chips. Multiplying the quantity of dried chips by the conversion ratio of 0.348 gives 1628.64 kg of bioethanol per ha. Thus, the processing of cassava cultivated on the test-site in Lam Dong has the potential to yield in 1628.64 kg of bioethanol per ha. This value can now be multiplied by the amount of marginal land (22,185 ha), giving 36,131,378.4 kg or 36,131.38 t of bioethanol, that can be produced, if all potential marginal sites would be cultivated with cassava. However, this is only 2 percent of the targets set out in Decision 177/2007 / QD-TTg, which aims to increase the output of ethanol and biodiesel to 1.8 million tons by 2025.

[42] Vera et al. (2022)
[43] Laban et al. (2018)
[44] Lorenz and Lal (2016)

In Scenario 2 of the LCA the difference between the g CO_{2eq}/MJ of gasoline (94.0) and bioethanol (77.67) was 16.33 g CO_{2eq}/MJ. So, 16.33 g CO_{2eq} are saved per MJ. The 1,628.64 kg bioethanol produced per ha cassava is then multiplied with the calorific value of ethanol (29.8 MJ/kg) to get 48,533.47 MJ saved per ha cassava. This value is then multiplied with 16.33 g CO_{2eq}/MJ to result in 792,551.60 g CO_{2eq} saved per ha cassava. This can then be multiplied with the amount of marginal land (22,185 ha) to calculate the potential GHG emissions savings of 17,582,757.25 g CO_{2eq} or 17,582.76 t CO_{2eq}. So, the potential GHG emissions savings if all potential marginal sites would be cultivated with cassava are 17,582.76 t CO_{2eq} with regard to Scenario 2. In 2022, Vietnam had CO_{2eq} emissions of 343.6 Mio t.[45] Therefore, the GHG emission saving potential of bioethanol produced from cassava cultivated on marginal lands in comparison to Vietnams total CO_2 is unfortunately low. Nevertheless, increasing the cultivation of cassava for bioethanol production on marginal areas still has the potential to save GHG emissions in Vietnam.
In July 2023, Vietnam's Prime Minister approved a new plan for the extraction of mineral resources (866/QD-TTg, Approval for Planning for Exploration, Extraction, Processing and Use of Minerals for The Period of 2021-2030 with a Vision to 2050) which will significantly increase the area required for bauxite mining after 2030 to 880-1400 ha/year). In the near future, Vietnam is therefore expected to see a significant increase in post-mining land, and therefore potential areas for energy crop cultivation and areas requiring recultivation. Thus, the amount of marginal land suitable for cassava cultivation for bioethanol production will eventually expand thereby increasing the above described GHG emission saving potential in the future.

[45] Statista (2024)

7 Conclusions

Vietnam has established a relatively comprehensive legal framework to promote energy transition, biofuel development and the reduction of GHG emissions for example through policy documents on climate change and the development of renewable energy and the transportation industry. Therefore, the current legislation in Vietnam is in favour of cultivating energy crops for bioethanol production to reduce GHG emissions. Nevertheless, further attention is needed to continue to build and strengthen the regulatory framework.

Vietnam still depends on fossil fuels like coal, crude oil and natural gas, which accounted for 80 percent of the total energy production in 2021. However, renewable energy sources like solar-, wind- and hydropower as well as biofuels and waste have increased in recent years and already made up 21 percent of the total energy supply in 2021. Thereby, Vietnam already achieved the goal of Resolution No. 55-NQ/TW and the National Strategy on Green Growth to reach about 15-20 percent of renewable energy sources in the total primary energy supply by 2030.

Nevertheless, the promotion of renewable energy in Vietnam is slowed down by influential energy enterprises supporting the existing energy system and decision-makers doubting its sufficient availability. In addition to that, the Vietnamese technology for producing bioethanol is old, lacks behind foreign standards and is often not competitive with conventional fossil fuels. Therefore, it is crucial to promote technology transfer and persuade decision makers that a well-established bioethanol industry reliably contributes to the country's energy security. Currently, only two out of seven ethanol facilities operate with a capacity of 56,808 and 98,750 tons per year due to an unstable supply of feedstock. So, Vietnam so far misses the goal of Decision 177/2007 / QD-TTg to increase the output of ethanol and biodiesel to 1.8 million tons by 2025. Furthermore, Chinas growing demand for cassava increases the export price in comparison to the domestic purchase price. As a consequence, Vietnams cassava exports increased by 22 percent between 2018 and 2021, thereby reducing the domestic supply. Negotiating cassava offtake contracts between farmers and ethanol manufacturers and capacity building on increasing their productivity might ensure a stable supply of feedstock to the ethanol facilities in the future. The Environmental Protection Tax applied on E5 is currently just 5 percent lower than on RON95. If the Vietnamese government wants consumers to prefer E5 gasoline, it needs to increase the price differences through import tariffs and CO_2 taxes on fossil fuels. However, Vietnam even imports bioethanol from the United States and South Korea and reduced the MFN import tariffs for bioethanol to 15 percent in 2020 thereby impeding the domestic production. Moreover, many consumers are still afraid that E5 gasoline might damage their engines and are not aware about the environmental benefits of biofuels. Awareness campaigns on biofuels might improve consumers demand in the long run.

The CPEP 2 project proves that the cultivation of cassava for bioethanol production on a post-mining site in Bao Lam district in the Lam Dong Province is possible. However, with a mean value of 8.42 t/ha (Scenario 1) the yield is far less than the mean cassava yield of the Bao Lam district (19 t/ha). Even if only the upper 25 percent of the values are taken into account, the mean yield is just 11.7 t/ha (Scenario 2). It is important to underline that 20-30 percent of the cassava roots were stolen before the harvest thereby distorting the results.

In Scenario 1 the mean yield of 8.42 t/ha of cassava is not sufficient to result in GHG emissions savings throughout the production process in comparison to fossil fuels. However, the use of E5 blended with cassava-based ethanol saves 3 percent GHG emissions in comparison with gasoline, because the fuel efficiency, of biofuels are higher than the one of gasoline. In Scenario 2 the mean yield of 11.7 t/ha of cassava is sufficient to result in GHG emissions savings throughout the production process and the use of E5 blended with cassava-based ethanol saves 3 percent GHG emissions in comparison with gasoline. In the production process of bioethanol, the main GHG emissions come from the cassava cultivation and the ethanol processing and the reduction potential at these two stages is still large. For example, higher yields through an optimized use of pesticides during cassava cultivation and the improved recovery of biogas from cassava wastewater for steam production for electricity during processing might further reduce GHG emissions per litre bioethanol produced. In fact, higher cassava yields of 17.5 t/ha in the CPEP 1 project resulted in 49 percent of GHG emission savings in comparison to the use of gasoline. This shows that higher cassava yields on post-mining sites are actually feasible and improve GHG emissions savings tremendously.

The production of bioethanol from cassava cultivated on post-mining sites and its potential to save GHG emissions are currently further inhibited, because only one bioethanol plant in Vietnam processes cassava chips leading to higher GHG emissions for transportation. Therefore, GHG emission might be reduced if there were more ethanol plants in operation for example in the northern part of Vietnam. Moreover, the ethanol plant in Dong Nai province has switched its input to maize, due to insecurities in cassava supply caused by high export prices. Therefore, growing maize instead of cassava in future projects might be another opportunity to upscale the recultivation of post-mining sites with energy plants. Lastly, there are a total of 22,185 ha of marginal areas suitable for growing cassava for bioethanol production in Vietnam, which will eventually increase, because Vietnam's Prime Minister approved a new plan for the expansion of extracting mineral resources in the future. Increasing the cultivation of cassava on current marginal areas has the potential to save 17,582,76 t CO_{2eq} and to support the country in achieving its goal to reduce GHG emissions by 92 percent until 2050.

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