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Different palm oil production systems for energy purposes and their greenhouse gas implications

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ABSTRACT

This study analyses the greenhouse gas (GHG) emissions of crude palm oil (CPO) and palm fatty acid distillate (PFAD) production in northern Borneo (Malaysia), their transport to the Netherlands and their co-firing with natural gas for electricity production. In the case of CPO, conversion to biodiesel and the associated GHG emissions are also studied. This study follows the methodology suggested by the Dutch Commission on Sustainable Biomass (*Cramer Commission*). The results demonstrate that land use change is the most decisive factor in overall GHG emissions and that palm oil energy chains based on land that was previously natural rainforest or peatland have such large emissions that they cannot meet the 50–70% GHG emission reduction target set by the *Cramer Commission*. However, if CPO production takes place on degraded land, management of CPO production is improved, or if the by-product PFAD is used for electricity production, the emission reduction criteria can be met, and palm-oil-based electricity can be considered sustainable from a GHG emission point of view. Even though the biodiesel base case on logged-over forest meets the *Cramer Commission's* emission reduction target for biofuels of 30%, other cases, such as oil palm plantations on degraded land and improved management, can achieve emissions reductions of more than 150%, turning oil palm plantations into carbon sinks. In order for bioenergy to be sustainably produced from palm oil and its derivatives, degraded land should be used for palm oil production and management should be improved.

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1. Introduction

Over the past decade, many industrialised countries have sharply increased the amount of biomass they import. This is primarily due to the fact that such countries introduced policies to stimulate renewable energy use and that imported biomass is often more cost-efficient than domestic biomass. Increasing global trade and consumption of bioenergy has been accompanied by a growing concern about the environmental, ecological, and social impacts of bioenergy production. This concern has been spurred by reports about bioenergy crop production causing deforestation and the

associated loss of biodiversity, greenhouse gas (GHG) emissions, displacement of forest people and related land conflicts, to name just a few. Southeast Asian palm oil, in particular, has been associated with major problems such as clear-cutting of natural rainforest, destruction of ecologically valuable peatland and instigation of social conflicts, and its sustainability has been intensely debated in many countries [1–4]. As a result of these unintended and undesired effects of bioenergy production, various initiatives have attempted to develop sustainability criteria in order to ensure sustainable bioenergy trade [5–9]. In Europe, such efforts began in Belgium where an energy company developed its own

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certification system that is widely accepted by Belgian authorities [5,6]; in the UK where, as part of the renewable transport fuel obligation, reporting guidelines on carbon and sustainability are being developed [7]; and in the Netherlands where the so-called *Cramer Commission* on sustainable production of biomass has recently finished its work [8]. The European Commission is also working on legislation to guarantee the sustainable production of biomass [9].

In all of these initiatives, the GHG balance is an important sustainability criterion because the presumed GHG emission savings compared to fossil energy are a key driver of increasing bioenergy consumption. However, it cannot simply be assumed that bioenergy results in GHG emission savings since both the land use change (LUC) associated with biomass production and inputs needed for such LUC like fossil fuels for machinery, fertiliser, and pesticides can generate GHG emissions [10,11]. LUC in particular has been found to strongly affect the GHG balance either by emissions from, for example, the net loss of standing biomass when natural rainforest is converted to other uses, or by sequestration of carbon from, for example, a net increase of soil carbon when degraded land is converted to bioenergy production [11–14].

Although methods for calculating GHG balances have been developed for the Belgian, British, and Dutch initiatives [5,15,16], several aspects of implementation and verification of this sustainability criterion remain debatable. Such unsettled aspects include the method of allocating emissions to by-products, the allocation period over which LUC emissions should be amortised and the choice of the fossil electricity reference system. Moreover, these methodologies have not yet been tested on specific production cases. Therefore, the main objectives of this study are (1) to analyse the GHG balance of specific palm-oil-based energy chains and (2) to study the effects on the GHG balance of the three above-mentioned unresolved methodological issues, as well as the effects of different reference land use systems and of different management options. In order to do so, the following chains are considered:

- (1) *CPO electricity chain*: production of crude palm oil (CPO) in northern Borneo, Malaysia, transport to the Netherlands and co-firing at a natural gas power plant in the Netherlands;
- (2) *PFAD electricity chain*: production of the palm oil derivative palm fatty acid distillate (PFAD) in northern Borneo, Malaysia, transport to the Netherlands and co-firing with natural gas for electricity production in the Netherlands; and
- (3) *Biodiesel chain*: using the CPO for the production of biodiesel in Malaysia and transporting the biodiesel to the Netherlands for use in vehicles [17].

The GHG emission calculations are based on the methodology developed by the *Cramer Commission* since, in order for the analysed chains to be considered sustainable, they will have to meet the *Commission's* criteria.

The remainder of the study is organised as follows: The methodology applied for calculating the GHG emission reductions of bioenergy compared to fossil reference systems

is described (Section 2), and the data input is presented (Section 3). Then, the results of the GHG analysis of the three chains, of their various cases and of the effects of the methodological choices are presented in Section 4, followed by a discussion of the results and the methodological choices (Section 5). Section 6 presents the study's final conclusions.

2. Methodology

This study determines the GHG emissions from CPO and PFAD-based electricity and CPO-based biodiesel production according to the Dutch *Cramer Commission* methodology for GHG calculations [16], which is based on a life cycle inventory and accounts for all GHG emissions that arise between initial land use conversion through final use of the palm-oil-based energy.

The three most important GHGs, carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O), are included. For comparing the emissions of these three gases, the concept of global warming potential (GWP) is applied following the guidelines of IPCC, allowing for a comparison of the radiative forcing of the different gases [18]. The other main GHGs (hydrofluorocarbons, perfluorocarbons, and sulphur hexafluoride) are not taken into account as they are insignificant in the bioenergy production chains.

The GHG emissions of by-products, which are used outside the system boundaries, are calculated on the basis of system extension. This approach assumes that the by-product generated can replace the same or a similar product that was produced from another feedstock. Due to this replacement, an emission credit for the avoided GHG emission from the original production of the product can be assigned.

The percentage of GHG emission reduction is calculated by dividing the difference in GHG emissions from the fossil and bioenergy chain by the emissions of the fossil reference system. The reduction percentage is measured against the standards set by the *Cramer Commission*, which requires an emission reduction of 50–70% for bioelectricity and 30% biodiesel in order for these to be considered sustainable [8]. A negative percentage of emission reduction refers to a bioenergy system that has larger emissions than the fossil energy system. A positive percentage of emission reduction refers to a bioenergy system that reduces GHG emissions compared to the fossil reference system. A percentage of emission reduction of more than 100% refers to a bioenergy system that sequesters more CO₂ than is emitted in terms of CO₂ equivalent throughout the production chain. The functional units are defined as production of 1 kWh of electricity for the electricity chains and 1 MJ fuel for biodiesel.

In addition to the percentage of GHG emission reduction, the emissions from palm oil energy chains are also expressed in terms of carbon payback time. This is the period of time that the bioenergy feedstock needs to be grown before the LUC emissions have been offset [19]. The carbon payback period is determined by dividing the net carbon loss from LUC per hectare by the amount of carbon saved per hectare and per year by the use of bioenergy (excluding LUC emissions).

For this study, case-specific data from a field visit of two plantations, two mills and one refinery in the Sandakan

region of northern Borneo, Malaysia are used. The field visit was conducted in connection with a Roundtable for Sustainable Palm Oil and *Cramer Commission* pre-audit by the certification body Control Union in February 2007. The plantations visited were well managed, demonstrated by their integrated pest management, waste minimisation and landfill practices, zero burning, and habitat conservation and restoration. Each plantation had its own mill on site, but the refinery was located in Sandakan, approximately 100 km from the plantations, from where CPO and its derivative products can be directly shipped abroad. The GHG emissions of the transesterification process are based on data from the literature because the case study did not include transesterification of CPO.

2.1. CPO electricity chain

The first step in the CPO electricity chain is the land use conversion necessary to establish an oil palm plantation, followed by the production of the fresh fruit bunches (FFBs), the milling and production of CPO, transportation of the CPO to the Netherlands, and CPO-based electricity production (Fig. 1). Each of these steps and the resulting GHG emissions and credits are described in more detail in the following sections.

2.1.1. Land use change

LUC refers to the conversion of one type of land to another (e.g. forestland to oil palm plantation). Such a conversion affects the carbon stocks of standing biomass, belowground biomass, soil carbon, and carbon stored in dead organic matter (DOM). Various reference land use systems are studied: logged-over forest (also referred to as “base case” because it resembles the case study), natural rainforest, peatland, and degraded land. The LUC emissions from aboveground biomass (AGB), DOM, and soil carbon stock changes are determined for each of the land use systems based on the Tier 1 methodology of the IPCC guidelines on GHG emissions from LUC [18].

The CO₂ assimilation at the oil palm plantation accounts for only the CO₂ that is fixed in the oil palm trunk and in the fronds that are not cut at harvest. This delineation is necessary so that it can be assumed that FFB and its products (CPO) and the by-products empty fruit bunches (EFB), palm kernel shells (PKS), and fibre are carbon neutral in the later steps of the production chain. FFBs and the fronds that are cut off at harvest are applied as organic fertiliser and dealt with in the following section.

For each unit of palm oil energy to account for its share of the GHG emissions from LUC and the assimilation of CO₂ by the oil palms, the net emissions from LUC are

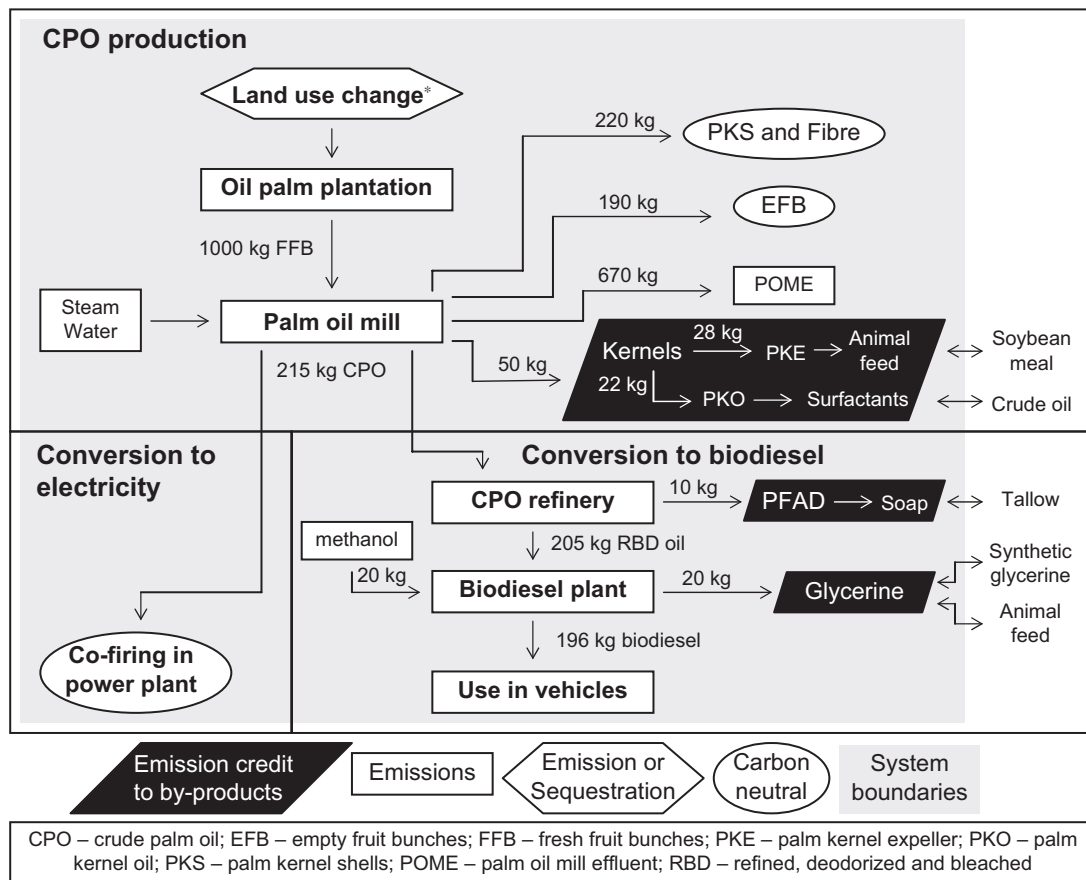


Fig. 1 – System boundaries of the two CPO-based chains with approximate mass flows and an overview of emission sources and credits. Not shown are the different transport stages that also cause GHG emissions. *Whether CO₂ is emitted or sequestered as a result of LUC depends on the land use reference system.

calculated by

$$\text{LUC emissions} = 3.7 \times [(\text{LUC C}/(T_{\text{LUC}} \times Y) - C_{\text{uptake}}/(T_{\text{plant}} \times Y)] \quad (1)$$

where LUC emissions are the net emissions from LUC ($\text{g CO}_2\text{-eq MJ}_{\text{CPO}}^{-1}$); 3.7 the molecular weight ratio of CO_2 to C (unitless); LUC C the loss of carbon (C) from LUC (C ha^{-1}); C_{uptake} the carbon uptake by oil palms during plantation lifetime (C ha^{-1}); T_{LUC} the allocation time period of LUC emissions (yr); T_{plant} the plantation lifetime (yr); and Y the energy yield ($\text{MJ}_{\text{CPO}} \text{ha}^{-1} \text{yr}^{-1}$).

For the situation in which peatland is drained and then planted with oil palm, the additional CO_2 and N_2O emissions from peat decomposition after drainage are determined according to the IPCC guidelines for LUC [18].

The displacement of prior crop production and the possible land use induced by the movement of prior crop production to other areas (indirect LUC) is not included in this study. However, this displacement may contribute significantly to the overall GHG emissions [20].

2.1.2. Oil palm plantation

Various GHG-emitting inputs (e.g. diesel and fertiliser) are needed for the production of FFB at an oil palm plantation. While most of the harvest is done manually, some machinery, farm equipment, and trucks for FFB transport require fossil energy and emit GHG. The GHG emissions from fossil energy are calculated by multiplying the amount of fuel needed per hectare of land by the emission factor of the fuel.

GHG emissions from the production of machinery and equipment, construction of buildings, and production and use of pesticides are disregarded as they are minor compared to overall emissions in the system [16].

Nitrogen (N) fertiliser applied at the oil palm plantations causes GHG emissions during its production and N_2O emissions from its application to the field. Only the GHG emissions from N fertiliser production are calculated here because the emissions from phosphate and potash fertiliser production were found to be much smaller than N fertiliser production [16]. The GHG emissions from N fertiliser production are calculated by multiplying the amount of a specific N fertiliser by the emission factor for producing that fertiliser.

The direct and indirect N_2O emissions from organic and inorganic N fertiliser application are calculated according to the IPCC guidelines for N_2O emissions from managed soils [18]. Since the organic fertilisers (EFB and fronds) are piled in thin layers on the ground, it can be assumed that they decompose aerobically and result in no additional GHG emissions.

The various GHG emissions from the plantation are then summed and converted to per unit of energy (MJ_{CPO}) by dividing the emissions by the FFB yield, the oil extraction rate (OER) and the energy content of CPO.

2.1.3. GHG emission flows at mill

At the mill, GHG emissions arise from fossil fuel use (calculated as determined in the previous section) and from the palm oil mill effluent (POME), while emission credits are given to by-products. For the latter, GHG emission credits for by-products are only given if the by-product is used to replace another product outside the system boundaries, as is the case

for kernels (Fig. 1). Kernels receive GHG emission credits because they are used to produce palm kernel oil (PKO), which can then be used for surfactant production, and palm kernel expeller (PKE), which is used as animal feed and is assumed to replace soy meal. It is assumed that PKO is a feedstock in the surfactant production of alcohol ethoxylates (AE) and that, as a final product, it replaces 3-mole AE from petrochemical feedstocks. A petrochemical-surfactant-by-PKO-surfactant displacement of 1:1 is assumed based on information given by Stalmans et al. [21]. Credit for PKO surfactant is calculated by first determining the emission factors of crude oil surfactants and PKO surfactants. The difference in emission factors is then multiplied by the amount of surfactants that can be replaced by PKO. The second by-product, PKE, is assumed to replace soybean meal as animal feed. The GHG emission credit for PKE is calculated by multiplying the difference in emission factor of soybean meal and PKE.

At the case study site, POME, i.e. the wastewater generated from clarification and other processing steps, is treated in open ponds in order to reduce its biological oxygen demand. During the anaerobic treatment, biogas with a composition of approximately 60% CO_2 and 40% CH_4 is generated [22]. The amount of carbon released as CO_2 and CH_4 is the same amount of carbon that had been sequestered during the growth of the FFB. Thus, the CO_2 from biogas is considered carbon neutral. In contrast, CH_4 from biogas has a higher GWP than the CO_2 that was initially taken up and therefore cannot be considered neutral in terms of GHG emissions. To account for the initial CO_2 uptake, the emission factor of CH_4 from POME treatment is taken to be the GWP of CH_4 ($23 \text{ t CO}_2\text{-eq t}^{-1} \text{ CH}_4$) minus the amount of CO_2 that was taken up by the oil palm but then released as CH_4 during POME treatment, i.e. $2.75 \text{ t CO}_2\text{-eq t}^{-1} \text{ CH}_4$. The GHG emissions from POME treatment are then calculated by multiplying this emission factor with the amount of CH_4 produced.

2.1.4. GHG emissions from CPO transport

GHG emissions from transport encompass the transport of CPO by trucks to the harbour, by ocean vessel to Rotterdam, the Netherlands, and by inland ship from Rotterdam to the Claus Power Plant (Maasbracht, the Netherlands). GHG emissions from transporting CPO are calculated by multiplying the emission factor by the distance for each transportation step, adding up those emissions and then dividing by the energy content of CPO.

2.1.5. GHG emissions from co-firing CPO

The Claus Power Plant, operated by Essent, uses a natural gas boiler and a conventional steam cycle, which allows co-firing of vegetable oils without major modifications to the system. Built in 1977, the Claus Power Plant has a low electrical efficiency compared to modern combined cycle natural gas power plants. The CO_2 emissions from co-firing CPO for electricity production are not accounted for in the GHG balance of CPO-based electricity as the CO_2 emitted is equal to the amount that had been taken up in producing the FFB.

2.1.6. Overview of CPO production cases

All emissions from the CPO electricity chain are converted to emissions per kWh by applying the electric efficiency of the

Claus Power Plant. CPO production is studied using various land use reference systems, methodological issues such as the allocation of land use emission over different time spans and different methods for allocating emissions to products and by-products, and management improvement options for the plantation and mill (Table 1). In each of the land use cases (cases 1–4), a different pre-conversion reference land use system is studied. In the management case (case 5), four management improvement options are studied in order to determine by how much the GHG emissions of the base case can be reduced. These options are:

1. Establishing new oil palm plantations on degraded land.
2. Reducing CH₄ emissions from POME: anaerobic digestion of POME takes place in a closed system so that the generated biogas can be collected more easily. In this case, CH₄ emissions from outdoor POME treatment and additional GHG emissions from replaced electricity production are avoided because the collected CH₄ can be burned for producing electricity. If the national electricity grid is close to the mill, surplus electricity could be fed into the grid, replacing electricity from other sources.
3. Increasing the oil yield by planting better tree varieties, improving harvesting techniques (e.g. timing and collection), and better management.
4. Applying more organic N fertiliser such as the nutrient-rich slurry from POME treatment.

In order to determine the effects of the different methodological choices, cases 6 and 7 account for different time periods over which the GHG emissions from LUC can be distributed. Cases 8–10 analyse the effects of different methods for allocating emissions.

2.2. PFAD electricity chain

CPO refining results in refined, bleached, and deodorised (RBD) oil as the main product or in its derivatives RBD stearin and olein. The only by-product of refining is PFAD, which results from filtering the fatty acids and amounts to less than 5% by weight of all processed CPO. PFAD is commonly used in producing soap, animal feed, plastics and other intermediate products for the oleochemical industry [23]. Additionally, its high energy content and the small modification that is needed to co-fire PFAD with natural gas or oil have contributed to its increasing use in power generation [24]. Fig. 2 illustrates the PFAD production chain, the various sources of GHG emissions and emission allocation to the RBD oil.

Although PFAD is considered a by-product, it is an important input for the oleochemical and animal feed industries. Therefore, this study includes the refining process in the PFAD production chain despite a differing suggestion from the Cramer Commission methodology [16]. Economic allocation of the GHG emissions from the refinery to PFAD

Table 1 – Description of CPO production cases

Chain #	Name of case	LUC: original land type	LUC emission: allocation period (years)	Allocation/system extension	CPO/PFAD production data
<i>Land use</i>					
1	Base case (logged-over forest)	Logged-over rainforest	25 ^a	System extension	Production data from case study
2	Natural rain-forest	Natural rainforest	25 ^a	System extension	Production data from case study
3	Degraded	Degraded land (grassland)	25 ^a	System extension	Production data from case study
4	Peatland	Peatland–forest cover	25 ^a	System extension	Production data from case study
<i>Management</i>					
5	Management improvement	Degraded land (grassland)	25 ^a	System extension	CH ₄ collection and electricity production, improved yields, increased organic fertiliser
<i>Method</i>					
6	13 years	Logged-over forest	13	System extension	Production data from case study
7	100 years	Logged-over forest	100	System extension	Production data from case study
8	Economic	Logged-over forest	25	Allocation by market price	Production data from case study
9	Mass	Logged-over forest	25	Allocation by mass	Production data from case study
10	Energy	Logged-over forest	25	Allocation by energy	Production data from case study

^a While the average lifetime of a plantation is 25 years, the productive lifetime is only 21–23 years because no fruits are produced in the first years. The unproductive years are accounted for by averaging the FFB yield over the plantation lifetime.

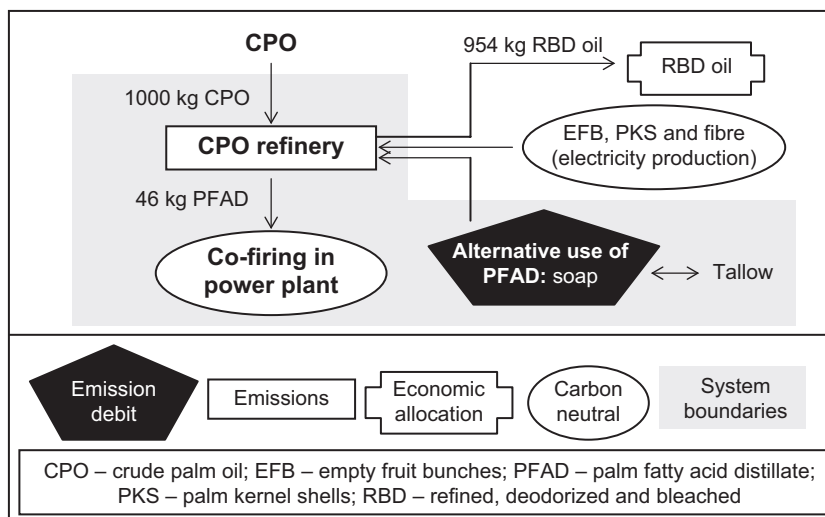


Fig. 2 – System boundaries of the PFAD electricity chain with approximate mass flows and an overview of emission sources/credits. Not shown are the different transport stages which also cause GHG emissions.

and RBD oil is applied because RBD oil is the main product and is not further used in the chain.

Refining of CPO consumes steam and electricity, and in the case study electricity is obtained from three sources: purchased from the grid (emissions equal the amount of electricity bought multiplied by the emission factor of average Malaysian electricity production); produced onsite from biomass, i.e. from combustion of EFB, PKS and fibre from independent mills (the biomass streams for steam and electricity production are carbon neutral because the emitted carbon is assumed to equal the amount sequestered by EFB, PKS and fibre during their growth); and produced onsite from fossil diesel in a generator (emissions equal the amount of fossil diesel multiplied by the emission factor of fossil diesel). Other inputs required in the refinery are bleaching earth and phosphoric acid, but both in such small quantities ($7 \text{ kg bleaching earth t}^{-1} \text{ CPO}$ and $500 \text{ kg phosphoric acid kt}^{-1} \text{ CPO}$) that the possible emissions of their production and use can be neglected.

Since PFAD is currently primarily used in soap and detergent production, this study assumes that this is the alternative use of PFAD. It is further assumed that the PFAD for soap production is substituted by tallow from beef production as both contain mainly long chain esters and that this substitution takes place at a rate of 1:1 (by weight). Because PFAD consists of the same fatty acids as CPO, it is assumed that the 1:1 tallow to palm oil substitution ratio as applied by Postlethwaite [25] is also valid for PFAD to tallow. The GHG emissions of the alternative PFAD use are then calculated by first multiplying the amount of tallow by the emission factor of tallow and then dividing the result by the energy content of PFAD.

PFAD is transported in the same manner as CPO, and due to similar energy content and density values of PFAD and CPO, it is assumed that the fossil energy requirements (and therefore GHG emissions) for PFAD transport to and within the Netherlands is the same as for CPO (see Section 2.1.4). CO_2 emissions from co-firing PFAD for electricity production are not accounted for as it is assumed that CPO is produced

sustainably and thus the CO_2 emitted in combustion equals the CO_2 assimilated during plant growth.

2.2.1. Overview of PFAD production cases

In addition to the PFAD base case (economic allocation, case 1) described above, three deviations are also considered. In cases 2 and 3, the emissions of the refinery are allocated on the basis of mass and energy, respectively. The case “PFAD no refinery emissions” (case 4) is based on the notion that PFAD can be treated as a residue rather than a valuable by-product. In that case only the emissions associated with PFAD treatment, transport or consumption need to be accounted for. Emissions from fossil energy consumption during refining are excluded in this case.

2.3. Biodiesel chain

An alternative to using CPO in electricity production is its use in the production of biodiesel. In the main process, base catalyst transesterification, the triglycerides of the oil are reacted with methanol to form methyl ester and glycerine. The biodiesel chain is composed of CPO production, CPO refining, transesterification of RBD palm oil and transport and storage at the various stages (Fig. 1). It is assumed that CPO is first refined and the resulting RBD palm oil is used in the transesterification process because the filtering out of free fatty acids increases the oil-to-PME conversion efficiency [26].

The GHG emissions of CPO production and transportation to the refinery/harbour are taken directly from the calculations described in Section 2.1, and the emissions of CPO refining are based on the description of CPO refining in the PFAD chain in Section 2.2. Since PFAD is not further used in the biodiesel chain, an emission credit is given. PFAD is assumed to replace tallow in soap production at a substitution ratio of 1:1. The emission credit is calculated by multiplying the emission factor of tallow with the amount of tallow that can be replaced by the production of 1 MJ of biodiesel.

RBD palm oil is transesterified at the refinery with the help of the catalyst sodium hydroxide (NaOH) and methanol.

The GHG emissions of transesterification are from the use of fossil energy and the production and use of fossil methanol and the catalyst; an emission credit results from the by-product glycerine, which is assumed to replace synthetically produced glycerine.

The GHG emissions of biodiesel transport to the Netherlands are taken directly from the calculations described in Section 2.1, and literature findings are used to determine the GHG emissions from biodiesel distribution within the Netherlands. While the use of biodiesel in vehicles is generally considered carbon neutral, the carbon atoms from fossil methanol still contribute to atmospheric emissions. The amount of these emissions is determined by assuming that one carbon atom in the empirical formula of PME ($C_{18}H_{35}O_2$) has its origin in fossil methanol [27,28].

The different CPO production systems and their effect on the GHG balance are also studied for the biodiesel chain. Here, only the variations in land use types and the management improvement cases are studied (cases 1–5). An additional case assumes that glycerine replaces wheat as animal feed rather than synthetically produced glycerine. This case is studied because replacing just five percent of fossil diesel with biodiesel in Europe would result in a glycerine production 30 times the size of current synthetic glycerine production in the EU [28]. Such an oversupply would cause the collapse of the glycerine market price—a development that is already being seen [29]. When the price for synthetic glycerine decreases, other uses of glycerine, such as animal feed, become more economically interesting [28]. While glycerine will only be used in animal feed if it is cheaper than alternatives, these two options of glycerine uses can be seen as the upper and lower limit of emission credits given and that, when new uses of glycerine are found over time, the emission credit is likely to be within these limits [28].

2.4. Fossil reference system

In order to determine the GHG emission reductions of the different bioenergy chains, a fossil reference system is defined, its life cycle emissions determined and the emissions compared to those of the bioenergy chains. In order to study the effect of how different reference systems may affect the emission reduction and whether meeting the reduction targets is affected by the choice of reference system, several reference systems are chosen for the electricity chains: Claus Power Plant (natural gas only), average Dutch electricity, a modern natural gas power plant, a coal power plant and average EU 25 electricity. In the case of diesel, the fossil reference system is fossil diesel from European production.

3. Input data

3.1. CPO electricity production

Data input to LUC emission calculations is based on the IPCC default values for different reference land use systems [18], except for the logged-over forest case where it is assumed that only 50% of the original biomass is left and that DOM carbon stock and soil carbon are similarly affected (Table 2).

The total amount of carbon assimilated at the plantation is based on the results of field experiments in Indonesia and is 95 tC ha^{-1} [30].

The FFB yield at the case study plantations was 31 t FFB per hectare in 2006. This value is high compared to the national average yield, likely due to the fact that the plantations are currently at peak production. The case study yield is not applied in this study because it does not account for the first years in which the plantation was unproductive nor for yield changes over time. Instead an average FFB yield of $25 \text{ tFFB ha}^{-1} \text{ yr}^{-1}$ over the lifetime of the plantation is assumed. The OER is 21.5% in the case study, a value also higher than the national averages, reflecting the good harvesting practices and management at the plantation. The energy content of CPO is assumed to be 36 MJ kg^{-1} [31].

The amount of fossil energy required at the plantation and the mill is taken from the case study and was found to be lower than data found in the literature [32]. The emission factors of the different fossil fuels are taken from the IPCC guidelines [18].

The amount of N fertiliser applied was determined at the case study plantation and is presented in Table 3. Although urea is drawn from several countries and ammonium sulphate from Japan, it is assumed that the emission factor from the production of both will be similar to those of European production [33]. The direct and indirect emissions from applying N fertiliser are based on the default values given by the IPCC for the emission factor of direct N_2O emissions from managed soils, of indirect emissions from managed soils through volatilisation and leaching or runoff, for the fractions of organic and synthetic N fertiliser that will volatilise as NH_3 or NO_x , and for the fraction of all N fertiliser added to the soil that is lost through leaching or runoff [18].

Kernels, produced at a rate of 240 kg t^{-1} CPO, are separated into 45% PKO and 53% PKE. Table 3 also presents the PKO emission credit, which is based on the average production of petroleum-based surfactants and PKO surfactants in Germany in 1996 [34], and the emission credit for PKE, which is based on average soybean production in the USA, import to and processing in the Netherlands [32].

The amount of CH_4 emitted during POME treatment at the mill is based on the case study POME yield of 3 m^3 POME per t CPO, a biogas yield of 28 m^3 biogas per m^3 POME [22] and a 40% share of CH_4 in the biogas [22].

Typical transportation types, fuels and emissions are taken from Damen and Faaij [35], and distances are applied as found in the case study (100 km dedicated truck transport of CPO from the mill to the harbour/refinery, 17 000 km ocean vessel transport to the Netherlands and 200 km dedicated transport by inland ships to the power plant).

The sensitivity analysis tests those parameters of CPO production for which large tests ranges were found. The parameters tested and the ranges applied are shown in Table 4.

3.2. PFAD electricity chain

Input data for CPO refining are based on the data obtained during the field visit and relate primarily to the energy consumption at the refinery (Table 5). Economic allocation of emissions related to the refinery are based on February 2007

Table 2 – Input data for LUC

Parameter	Unit	Value	Source
Aboveground biomass (AGB) before land conversion			
Natural rainforest	t dm ha ⁻¹	350	[18]
Logged-over forest ^a	t dm ha ⁻¹	175	[44]
Degraded land (<i>Imperata cylindrica</i>)	t dm ha ⁻¹	6.2	[18]
AGB at oil palm plantation after 25 years	t dm ha ⁻¹	118	[30]
Carbon fraction			
Natural rainforest	kg C t ⁻¹ dm	490	[18]
Palm tree	kg C t ⁻¹ dm	400	[30]
Grassland	kg C t ⁻¹ dm	400	[30]
C stocks of litter and dead wood			
Before conversion	t C ha ⁻¹	2.1	[18]
After conversion	t C ha ⁻¹	0	[18]
Palm plantation	t C ha ⁻¹	5.9	[30]
Soil organic C			
Reference (low activity clay soils)	t C ha ⁻¹	60	[18]
Oil palm plantation ^b	t C ha ⁻¹	40	[30]
Land-use system, management, input stock change factors	Dimensionless	1.0	[18]
Emission factor			
C from drained peatland	t C ha ⁻¹ yr ⁻¹	10.7 ^c	[18]
N ₂ O-N drained peatland	kg N ₂ O-N ha ⁻¹ yr ⁻¹	8	[18]

dm—dry matter.

^a Reducing AGB due to logging can range from 22% to 67% [44]. Here, 50% of the original biomass is assumed.

^b It is assumed that 50% of the soil carbon found in the first 100 cm is stored in the upper 30 cm.

^c In the IPCC guidelines, CO₂ emissions from peat oxidation depend on the original land type and the land type it is being converted to since different land types have different drainage depth requirements. For cropland (needing deeper drainage), a value of 20 t C ha⁻¹ yr⁻¹ is assumed. However, if the drainage is shallower, such as for perennial tree systems, the emission factor for forest management of organic soils may be assumed, for which the IPCC gives an emission factor of 1.36 t C ha⁻¹ yr⁻¹ [18]. The drainage depth of oil palm trees is commonly 60 cm (considered medium to shallow drainage) but can range from 30 cm to 2 m depending on the local conditions [45]. In this study, the average of the two emissions (10.7 t C ha⁻¹ yr⁻¹) is assumed.

prices for RBD oil and PFAD as listed by the Malaysian Palm Oil Board [36]. Regarding the emissions of the *alternative use* of PFAD, the emission factor of tallow (107 kg CO₂-eq t⁻¹ tallow) is based on the life cycle inventory of tallow production in Switzerland conducted by Nemecek et al. [37].

3.3. Biodiesel chain

Since no data on the transesterification of palm oil were collected during the field visit, the data used are based completely on the literature and described in Table 5. The energy requirement of CPO transesterification is based on general vegetable oil transesterification [29]. The amount of methanol required (100 kg t⁻¹ RBD oil) and the amount of crude glycerine produced (100 kg t⁻¹ RBD oil) is based on Choo et al. [38], while the amount of NaOH (6 kg t⁻¹ RBD oil) required for transesterification is taken from a GHG balance analysis of rapeseed oil methyl ester [39] assuming that this value also holds for PME because of the almost identical process and conversion efficiency [29]. The emission factor of methanol [33], NaOH [40], synthetically produced glycerine [41] and wheat as animal feed [42] are all based on typical production in Europe, which is assumed to be comparable to that in Malaysia. Emissions from distribution in the Netherlands is assumed to be the same as for fossil diesel [28].

Emissions from the use of biodiesel in the Netherlands are based on average emissions of biodiesel found in the Tank-to-Wheels study [28].

3.4. Fossil reference systems

The emission factors for the different fossil reference systems are taken from other life cycle inventory studies and databases and are presented in Table 6.

4. Results

4.1. CPO electricity chain

The breakdown of emissions by components shows that the most important source of GHG emissions is LUC, even when the CO₂ uptake of the oil palm plantation is accounted for (Fig. 3). Conversion of peatland creates not only direct emissions from LUC (carbon stock changes in biomass, soil and DOM), but also emissions from the oxidation of organic peat soils, which are by themselves as large as the emissions from the entire rest of the chain. In contrast, CPO-based electricity from degraded land as well as from incorporating

Table 3 – Input data for CPO production

Parameter	Unit	Value	Source
EF fertilizer production			
Ammonium sulphate	kg CO ₂ -eq kg ⁻¹ N produced	2.7	[33]
Urea	kg CO ₂ -eq kg ⁻¹ N produced	1.3	[46]
EF fertilizer application			
Ammonium sulphate	kg N ha ⁻¹ yr ⁻¹	70	Case study
Urea	kg N ha ⁻¹ yr ⁻¹	79	Case study
Organic fertiliser (fronds and EFB)	kg N ha ⁻¹ yr ⁻¹	31	Case study
AE PKO production	t AE PKO t ⁻¹ PKO	1.7	[34]
EF AE PKO ^a	t CO ₂ t ⁻¹ AE PKO	2.7	[34]
EF AE petrochemical ^a	t CO ₂ t ⁻¹ AE petrochemical	5.2	[34]
EF average surfactant mix ^b	t CO ₂ t ⁻¹ surfactant mix	3.4	[34]
EF soy bean meal	kg CO ₂ -eq t ⁻¹ soy bean oil	550	[32]
EF PKE	kg CO ₂ -eq t ⁻¹ PKE	155	Own calculations ^c
Energy for kernel crushing			
Electricity from grid	kWh t ⁻¹ kernel input	85	[47]
Diesel for steam production	dm ³ t ⁻¹ kernel input	19	[47]

EF—emission factor.

^a GHG emission factors of surfactants are based on Patel [34], who determines CO₂ emissions only, because only limited information is available on CH₄ and N₂O emissions from surfactant production.

^b In the base calculation it is assumed that one unit of PKO-based surfactant replaces one unit of petrochemical surfactant. However, it may be the case that it replaces one average-mix unit of alcohol ethoxylates (AE petrochemical, AE PKO, AE CNO). The effects of such a change will be taken into account in the sensitivity analysis of emissions from CPO production.

^c The emission factor of PKE includes the emissions from the energy input for kernel crushing that is allocated to PKE based on market prices and the emissions from transporting PKE to the Netherlands, where it substitutes soy bean meal.

Table 4 – Parameters and ranges for the sensitivity analysis of the CPO base case

Parameter	Unit	Low	Base case	High	Source low; source high
AGB natural rainforest	t dry matter ha ⁻¹	280	350	520	[18]; [18]
% AGB lost through logging	%	22	50	67	[44]; [44]
Soil carbon pre-conversion	t C ha ⁻¹	24	48	72	± 50% variation
FFB production	t FFB ha ⁻¹ yr ⁻¹	19	25	31	[36]; [36]
EF production					
Ammonium sulphate	kg CO ₂ -eq kg ⁻¹ N	0.9	2.7	7.6	[46]; [46]
Urea	kg CO ₂ -eq kg ⁻¹ N	0.9	1.3	4	[46]; [46]
EF N ₂ O from managed soils	kg N ₂ O-N t ⁻¹ N	3	10	30	[18]; [18]
Diesel consumption at plantation	GJ ha ⁻¹ yr ⁻¹	2.1	3.2	5.1	[48]; [32]
Oil extraction rate	%	19	21	23	[36]; [36]
Methane emissions from POME	m ³ CH ₄ t ⁻¹ CPO	19.5	33.6	66.2	[49]; [22]
Emission credit					
Surfactant	t CO ₂ t ⁻¹ surfactant	3.4	5.2	–	[34]; –
Soybean meal	kg CO ₂ t ⁻¹ soy bean meal	275	550	825	± 50% variation

EF—emission factor.

other management improvement options can even take up more CO₂ than emitted in the whole production chain (Fig. 3).

A sensitivity analysis is conducted for individual parameters of CPO production for which the literature showed large ranges and deviations from the case study. The sensitivity analysis shows that the GHG balance is most affected by the pre-conversion AGB, percentage of AGB lost through logging and soil carbon content (Fig. 4). The results

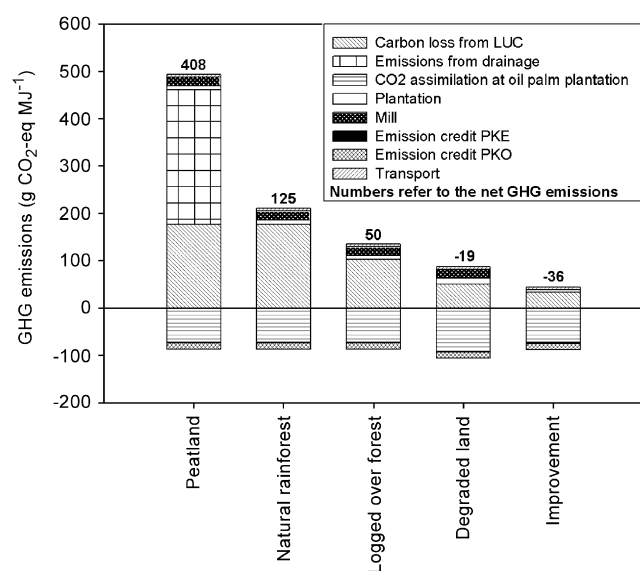
are also, but to a lesser extent, sensitive to the amount of CH₄ produced during POME treatment and to FFB yields. Additionally, the emission credit that is given to PKO has a large effect on the overall emissions; if the PKO-based surfactants do not replace fossil-based surfactants, as is assumed in the base case, but rather an average mix of surfactants, the overall emissions would increase by nearly 20% (Fig. 4). In contrast, the emission credit given to PKE used as animal feed

Table 5 – Parameters and values for PFAD electricity chain and biodiesel chain

Parameters	Unit	Value	Source
PFAD electricity chain			
PFAD production rate	kg PFAD t ⁻¹ RBD palm oil	50	Case study
Energy content PFAD	MJ kg ⁻¹	38.5	[50]
<i>Energy requirements at Refinery</i>			
Diesel	MJ t ⁻¹ CPO	200	Case study
Biomass	MJ t ⁻¹ CPO	650	Case study
Electricity from grid	kWh t ⁻¹ CPO	23.4	Case study
Biodiesel chain			
PME density	kg m ⁻³	880	[51]
Conversion efficiency (CPO–PME)	kg PME t ⁻¹ CPO	960	[38]
Energy requirements transesterification	kWh m ⁻³ PME	250	[29]
Methanol emissions	kg CO ₂ -eq t ⁻¹ methanol	786	[33]
Catalyst (NaOH)	kg CO ₂ -eq kg ⁻¹ NaOH	1.2	[40]
Emissions from synthetic glycerine	kg CO ₂ -eq kg ⁻¹ glycerine	9.6	[41]
Emissions from wheat as animal feed	kg CO ₂ -eq t ⁻¹ feed	744	[42]
Distribution of biodiesel in NL	g CO ₂ -eq MJ ⁻¹ PME	1.1	[28]
End use of biodiesel	g CO ₂ -eq MJ ⁻¹ PME	5.9	Own calculations based on [28]

Table 6 – Life cycle GHG emissions of the reference fossil energy chains

Parameter	Unit	Value	Source
Claus power plant	g CO ₂ -eq kWh ⁻¹	559	Provision: own calculations based on [41]; Use [52]
Dutch average electricity mix (2000)	g CO ₂ -eq kWh ⁻¹	615	[32]
Modern NG power plant	g CO ₂ -eq kWh ⁻¹	400	[41]
Dutch coal power plant	g CO ₂ -eq kWh ⁻¹	1000	[32]
EU25 average electricity mix (2000)	g CO ₂ -eq kWh ⁻¹	486	[41]
Fossil diesel	g CO ₂ -eq MJ ⁻¹	88	Provision [28]; Use [18]

**Fig. 3 – GHG emissions of CPO delivered to power plant, by source.**

hardly affects the results. The factors that are most uncertain are the emission factors for fertiliser production, i.e. ammonium sulphate and urea production, and the N₂O emission

factor from nitrogen fertiliser application. However, despite this uncertainty, the emission factors of ammonium sulphate and urea production scarcely affect overall emissions. In contrast, the range of the N₂O emission factor from managed soils as given by the IPCC [18] can cause the overall GHG emissions to increase or decrease by more than 10%.

4.2. PFAD electricity chain

The total GHG emissions of PFAD-based electricity production are only one-sixth of the emissions of the CPO base case (Table 7).

4.3. Biodiesel chain

The results of the biodiesel GHG emission analysis show that the emissions of CPO used for biodiesel are in most cases lower than when CPO is used for electricity (Table 8). The main reason for this is the additional processing step that, using only a relatively small amount of fossil energy, produces glycerine as a by-product that, if synthetically produced, is very energy intensive and, therefore, receives a high emission credit. When glycerine replaces animal feed instead of synthetic glycerine, GHG emissions of biodiesel nearly double.

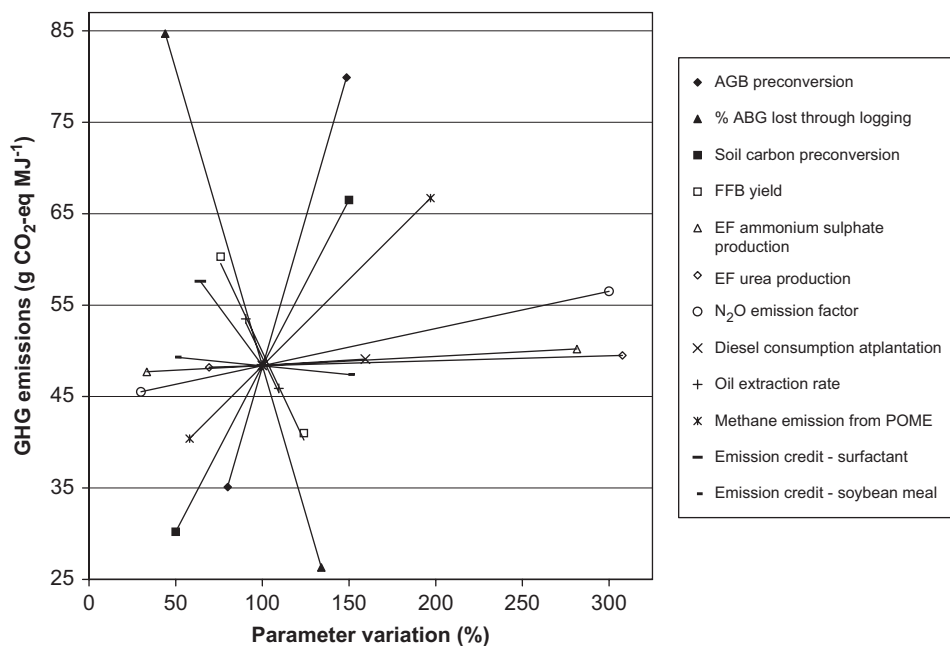


Fig. 4 – Sensitivity of GHG emissions of base case (logged-over forest).

Table 7 – GHG emissions of the PFAD production chain, by component (all values are in $\text{g CO}_2\text{-eq MJ}^{-1}$ PFAD)

	PFAD base case	Mass allocation	Energy allocation	No refinery emissions
Refinery	1.6	2.2	2.2	0
Alternative use	2.8	2.8	2.8	2.8
Transport	4.2	4.2	4.2	4.2
Total	8.6	9.2	9.2	7.0

Table 8 – GHG emissions of the biodiesel chain compared to the CPO electricity chain

	Emissions ($\text{g CO}_2\text{-eq MJ}^{-1}$ CPO)		Emission reduction (%)		Payback time (years)	
	Biodiesel	CPO electricity ^a	Biodiesel	CPO electricity ^a	Biodiesel	CPO electricity ^a
Peatland forest	391	407	–337	–528	169	320
Natural rain forest	107	123	–20	–90	30	57
Base case	32	48	65	25	8	16
Base case (animal feed)	61	n/a	32	n/a	10	n/a
Degraded land	–51	–35	157	154	n/a	n/a
Improvement	–53	–37	159	156	n/a	n/a

^a Compared to Dutch average electricity production.

4.4. GHG emission reductions and carbon payback time

The base case can meet the Cramer Commission's 50% emission reduction target only if it is compared to coal electricity, while palm oil electricity from degraded land and from CPO production with improved management results in emission reductions of more than 70%, regardless of the fossil reference system it is compared to (Fig. 5). The GHG emission reductions of CPO electricity from land that was previously natural rainforest or peatland are negative, indicating that the use of CPO from these cases results in more emissions than

the fossil reference systems. In contrast, PFAD-based electricity has a large potential for reducing GHG emissions (Fig. 5).

Palm-oil-based biodiesel can result in GHG emission savings above 60% if glycerine replaces synthetic glycerine and if the palm oil is not from converted natural rainforest or peatland (Table 8). Emissions reductions from biodiesel are significantly higher than from CPO in power production due to the emission credit given to the biodiesel by-product glycerine and due to the relatively low electric efficiency of the Claus Power Plant. If glycerine is used to displace animal

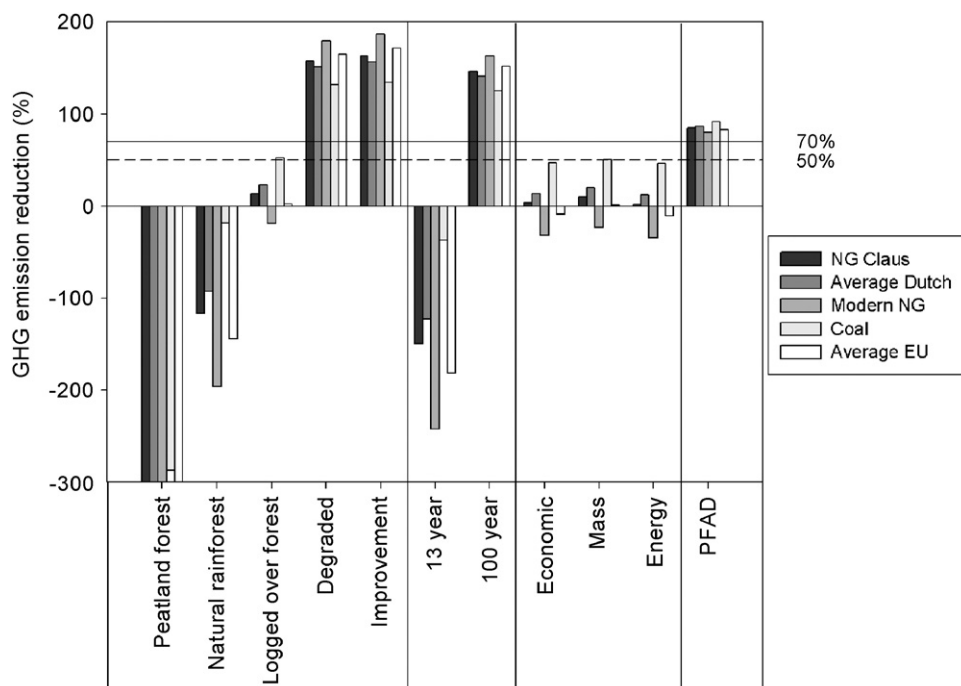


Fig. 5 – GHG emission reductions of various CPO and PFAD electricity production chains compared to different fossil reference systems.

feed rather than synthetic glycerine, the emission reduction drops to 32%, which is still slightly higher than the bioelectricity base case.

The carbon payback time is determined for those CPO electricity and biodiesel chains with reference land use cases in which a net carbon loss from LUC towards oil palm plantations is observed. High carbon payback periods for peatland and natural rainforest confirm that palm oil from these land types cannot be considered sustainable. In contrast, the base case on logged-over forest could contribute to GHG emission savings after eight (biodiesel) to 16 years (electricity) of palm oil production (Table 8).

4.4.1. Methodological issues

The effects of three methodological issues on the GHG balance are presented next for the CPO electricity chain: the allocation period for LUC emissions, the method of allocating emissions to the different products and the choice of fossil electricity reference system. These issues are expected to have a similar effect on the two other chains and are therefore not further elaborated here.

The allocation period for LUC emissions has a large impact on whether GHG emission reduction targets may be achieved (Fig. 5). A shorter allocation period of 13 years results in negative GHG emission reductions in the base case. This was also found to be true for the other LUC cases, except when degraded land is planted with palm oil. An allocation period of 100 years results in emission reductions of more than 100% in the base case and at least 70% in other LUC cases. An exception is the peatland case, which has a negative emission reduction even with an allocation period of 100 years.

In contrast, neither the method for allocating emissions from by-products nor the choice of a fossil electricity

reference system has a significant effect on the GHG emission reduction. Fig. 5 illustrates that, although different fossil electricity reference systems do cause some variation in the bioelectricity chains' overall emission reductions, the variation is generally not sufficient to affect whether the 50–70% emission reduction target is reached. Only when a case is already borderline does the fossil reference system affect whether the reduction target is met.

5. Discussion

GHG emissions from LUC were calculated according to the Tier 1 methodology of the IPCC guidelines for national GHG inventories, which assumes that LUC does not cause a carbon stock change in belowground biomass [18]. However, large amounts of carbon may actually be stored in belowground biomass. While not enough data was available to have included this aspect in the main analysis of this study, it is possible to compare the carbon in belowground biomass of natural rainforest to that of grassland and oil palm plantation (based on IPCC default values for belowground biomass to AGB for natural rainforest and tropical grassland [18] and on data from the field experiments of Syahrudin [30]). The comparison reveals that carbon in belowground biomass is 41 tC ha^{-1} for natural rainforest, 5 tC ha^{-1} for grassland and 19 tC ha^{-1} for oil palm plantation, indicating that the assumption that LUC does not cause a carbon stock change in belowground biomass is not valid. However, the inclusion of carbon in belowground biomass would not alter the general outcome of this analysis but would amplify the result that CPO production on degraded land can act as a carbon sink and that converting natural rainforest to oil palm plantations results in higher GHG emissions than a fossil-based system.

Other important aspects of the LUC issue are the displacement of prior crop production and the possible LUC induced by the movement of prior crop production to other areas or the replacement of prior crop products by alternative resources. Reinhardt et al. [43] have shown that replacement of prior crop products, such as converting a coconut plantation to an oil palm plantation and substituting coconut oil with fossil oil surfactant and coconut press cake for fodder with soybean meal, causes GHG emissions that are even larger than when palm oil is produced on land that used to be natural rainforest. In such cases, *Cramer Commission* GHG emission targets could not possibly be met. Although the *Cramer Commission* has thus far excluded GHG emissions from indirect LUC from the movement of prior crop production, its sub-commission on the GHG calculation tool advises the immediate initiation of a macro-level monitoring scheme in order to investigate the effects of production displacement on the GHG balance [16]. Searchinger et al. [20] recently emphasised the need for including indirect LUC in the GHG balance calculations, concluding that a focus on direct LUC would produce positive results for many chains that, when implemented, would lead to less or possibly no GHG emission reductions in reality.

The feasibility of the suggested management improvement options should also be addressed. Of the four suggested improvement options, the increased yield option is economically most interesting because of the increased income it implies. The application of more organic fertiliser is already becoming more common in Malaysia due to a new law that prohibits the direct discharge of treated POME into waterways, causing more of the nutrient-rich slurry to be spread on the plantation. However, the most effective option for reducing GHG emissions, planting oil palm on degraded land, is rare due to the fact that degraded land does not provide initial capital from timber extraction (as does natural

rainforest), entails higher establishment costs and possibly reduced yields. The fourth improvement option, which is the second most beneficial option for GHG emission reduction, relates to the collection of CH₄ from POME treatment. Currently, this option is not commonly found in the Malaysian palm oil industry, but interest in POME biogas collection and electricity production has been rising rapidly because of the possibility of getting certified emission reductions through CDM projects [22]. In addition to these improvement options, other options for reducing GHG emissions should be identified and further studied.

PFAD-based electricity was found to have very low emissions compared to both fossil reference systems and to CPO-based electricity production. The most important reason for this outcome is that PFAD is treated as a by-product so only those emissions that are generated in direct connection with PFAD processing, transport and use are accounted for. Based on the mass balance of a refinery, it makes sense to treat PFAD as a by-product. However, this choice may be debatable given that PFAD is a valuable product for the oleochemical and animal feed industries. In addition, by only including emissions from the refinery process onward, PFAD-based electricity from unsustainably produced CPO could be considered sustainable. Resolving this inconsistency requires a general discussion about when to consider a product a by-product only and, in this case specifically, how to account for the possibility that unsustainable CPO may be used for PFAD production.

Based on the results of the GHG emission analysis of the electricity chains, a simple decision tree was made for determining the level of GHG emission reductions that can be reached under different conditions (Fig. 6). This decision tree is simplified and actual compliance with GHG emission criteria depends on local conditions.

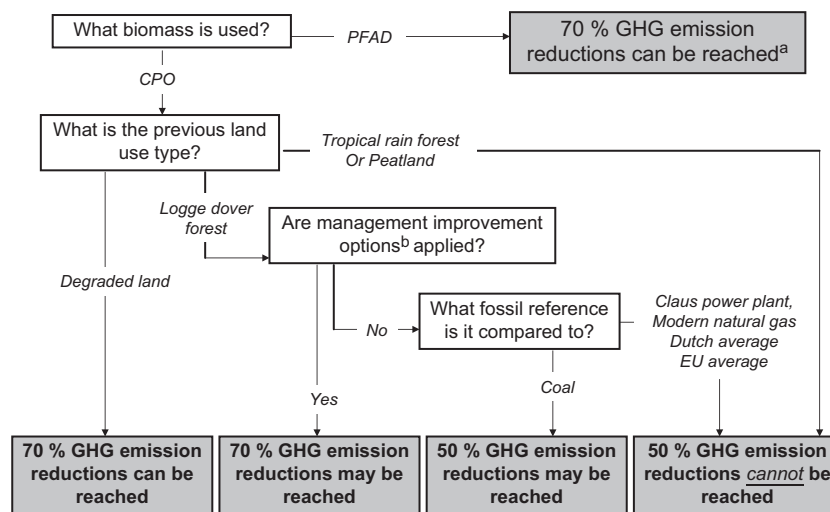


Fig. 6 – A simple decision tree for determining what emission reductions can be achieved from palm-oil-based electricity production. ^a Assuming that PFAD is treated as a by-product. ^b The improvement options refer to (1) establishing a new plantation on degraded land, (2) increasing FFB yields, (3) treating POME in closed conditions and collecting and burning CH₄ for electricity production and (4) applying slurry from POME treatment to the plantation as organic fertiliser.

6. Conclusions

This study found that palm oil energy chains based on former natural rainforest or peatland have such large emissions that they cannot meet the 50–70% GHG emission reduction target set by the *Cramer Commission*. The case study, palm oil production on logged-over forest, can only meet the emission reduction target of 50% if compared to coal-based electricity production. However, if CPO production takes place on degraded land, the management of the production of CPO is improved (including the use of degraded land for palm oil production), or if the by-product PFAD is used for electricity production, the criteria can be met, and palm-oil-based electricity can be considered sustainable from a GHG emission point of view. Even though the biodiesel base case on logged-over forest can meet the *Cramer Commission's* emission reduction target for biofuels of 30%, other cases, i.e. oil palm plantations on degraded land and improved management, can achieve emissions reductions of 150% or more and can turn oil palm plantations into carbon sinks.

This study demonstrates that LUC is the most decisive factor in overall GHG emissions and thus may not be neglected in GHG emission calculations of palm-oil-based energy or any other type of bioenergy. Related to LUC emissions is the issue of how to deal with PFAD-based electricity that is considered sustainable with respect to GHG emissions but that originates from unsustainably produced CPO. This issue requires more detailed discussion as it is also relevant for all other residues used for bioenergy. Another important factor in overall GHG emissions from palm-oil-based energy production is the allocation period for LUC emissions. A variation in the allocation period from the 25 years in the base case to 13 years results in negative GHG emission reduction percentages in all cases except the degraded land and the improved management cases. Conversely, an extension of the allocation period to 100 years leads to all but one case (peatland) meeting the *Cramer Commission* targets. As a result, even the natural rainforest case would be considered sustainable from a GHG emission point of view. The fact that the results can be significantly altered by varying the length of the allocation period for LUC emissions means that an appropriate time period must be selected when evaluating the GHG emission reduction potential of bioenergy.

Given these considerations, the study concludes that in order for bioelectricity and biodiesel to be sustainably produced from palm oil and its derivatives, only degraded land should be used for palm oil production and plantation management should be improved.

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