Environ Dev Sustain (2013) 15:429–479
DOI 10.1007/s10668-012-9387-z

Recalculating GHG emissions saving of palm oil biodiesel

Gernot Pehnelt · Christoph Vietze

Received: 26 June 2012 / Accepted: 25 August 2012 / Published online: 6 October 2012

Abstract In 2010, the Renewable Energy Directive (RED) came into force in the EU and establishes a framework for achieving legally binding greenhouse gas (GHG) emission reductions. Only sustainable biofuels can be counted towards Member State targets. The aim of this paper is to calculate realistic and transparent scenario-based CO_2-emission values for the GHG emissions savings of palm oil fuel compared with fossil fuel. Using the calculation scheme proposed by the RED, we derive a more realistic overall GHG emissions saving value for palm oil diesel by using current input and output data of biofuel production (e.g. in South-East Asia). We calculate different scenarios in which reliable data on the production conditions (and the regarding emission values during the production chain) of palm oil diesel are used. Our results indicate values for the GHG emissions savings potential of palm oil biodiesel not only above the 19 % default and 36 % typical value published in RED but also above the 35 % sustainable threshold. Our findings conclude the more accurate GHG emissions saving value for palm oil feedstock for electricity generation to be 52 %, and for transportation biodiesel between 38.5 and 41 %, depending on the fossil fuel comparator. Our results confirm the findings by other studies and challenge the official typical and default values published in RED. As a result, the reliability of the Directive to support the EU's low-carbon ambitions is being undermined, exposing the EU and commission to charges of trade discrimination and limiting the ability of Member States to achieve their legally binding GHG emission reductions.

Keywords Biofuel · Palm oil · Biodiesel · Renewable energy directive · Typical values · Default values · GHG emissions

G. Pehnelt
Independent Research Institute GlobEcon, Johann-Friedrich-Str. 25, 07745 Jena, Germany
e-mail: gp@globecon.org

G. Pehnelt · C. Vietze (✉)
Department of Economics, Friedrich-Schiller-University of Jena,
Carl-Zeiss-Strasse 3, 07743 Jena, Germany
e-mail: christoph.vietze@uni-jena.de

C. Vietze
EconEcolDev, Dornburger Str. 135, 07743 Jena, Germany

JEL classification F14 · F18 · O13 · Q01 · Q15 · Q27 · Q56 · Q57

1 Introduction

The European Union (EU) introduced an ambitious renewable energy policy in 2003, which has been further elaborated since then. The main document of this policy is the Renewable Energy Directive (RED). The Directive emphasises the EU's commitment to cut emissions by at least 20 % of 1990 levels by 2020. Proposed measures include improvements in energy efficiency as well as a binding target to increase the share of renewable energy by 2020 with 20 % renewable energy sources in total EU energy consumption. The share of renewable sources in EU road transport (i.e. biofuels) is required to reach at least 10 % by 2020.

The EU introduced certain sustainability criteria for the production and use of biofuels. One requirement of the EU Renewable Energy Directive for sustainable biofuels is that "there should be no damages to sensitive or important ecosystems while cultivating energy feedstocks" (EU 2009). This includes the absence of conversion of land with high biodiversity value and the conversion of land with high carbon stock. Another critical criterion refers to the greenhouse gas (GHG) emissions saving potential of biofuels. The Directive requires that the greenhouse gas emissions associated with production and use of biofuels are at least 35 % lower than those associated with production and use of conventional fuels. This threshold will rise to 50 % by 2017 and will increase further to 60 % in 2018. In order to calculate these GHG emissions saving ratios, the RED requires that the whole production chain from cultivation of the feedstock up to use of the biofuels is considered.

The most comprehensive approach to consider all stages of the production and use of biofuels and to evaluate the ecological impact of biofuels would be a detailed and well-founded life cycle assessment (LCA). LCA analyses the environmental flows related to a product or a service during all life cycle stages, from the extraction of raw materials to the end of life. Despite the growing interest in such studies, there are still relatively few LCA studies on biofuels and most of them focus on products and conditions in the EU or North America. One reason for that is the high uncertainty regarding the very methodology and data quality. Since it is an integral part of any comprehensive LCA to take into account the various co-products and side-effects of the activities associated with the production, transportation, commercialisation and consumption of the product under consideration, it has to be decided what exactly should be integrated into the analysis and how it should be measured with respect to the long-term (side-) effects over the full life cycle of the very product. The more co-products, allocation and distribution effects, environmental, economic and social issues one tries to consider in the course of LCA, the more complex the whole process becomes. With every single issue integrated into the analysis the variability regarding the assumptions, model structure and data quality, and—not least—the more blurred the results get. That is why it is neither possible to take into account every single effect a product or service might have over its full life cycle, nor is it appropriate with respect to the transparency and explanatory power of the models and results.

That is why it necessary to somehow limit the complexity of the underlying model by setting a clear cut system boundary and concentrate on the main inputs and outputs associated with the production and consumption of the very product. In the case of the biofuels, this includes the energy balance of the full process covering residuals and co-products. So-called well-to-wheel (WTW) studies are an appropriate and accepted way to

analyse the energy balance and carbon footprint of biofuels. In order to compare fossil and alternative fuels, they have to include the direct emissions of gasoline or diesel during the use phase in the motor combustion (tank-to-wheel/TTW) as well as indirect emissions associated with the production and transportation of the respective fuel (well-to-tank/WTT).[1]

Although the full process within the system boundary of production and consumption of many biofuels is basically well-known, reports on biofuels using LCA-like methods usually show a serious lack in transparency with respect to methodological details and assumptions such as specific yields, conversion technologies, inputs and outputs as well as the treatment of co-products and the respective allocation method (Menichetti and Otto 2009). Consequently, due to serious measurement problems, methodological differences, the lack of transparency and other uncertainties related with LCA, the results of published studies regarding the environmental effects—for example, the carbon footprint—of biofuels are far from conclusive and show tremendous differences, both quantitatively and qualitatively.

For instance, there is a remarkable difference between the calculation of carbon reduction performance of palm oil–based biofuel by the EU and a range of scientific studies. In calculations by the EU, the default GHG emissions reduction by palm oil–based biofuels fail the given threshold of 35 per cent under certain assumptions whereas quite a few studies yield very different results. Among other issues, this has been documented and discussed in a previous paper by Pehnelt and Vietze (2009). Given the noteworthy results of this previous study, we recalculate the GHG emissions saving value for palm oil as a source for biodiesel in order to further assess the carbon footprint of palm oil and to overcome the lack in transparency in existing publications on the very issue.[2]

2 Production process

2.1 Cultivation of oil palm/plantation

The oil palm (*Elaeis guineensis*) is a perennial crop with a height of approximately 10 metres but can grow up to 20 m tall. Oil palms have a (productive) lifetime of more than 30 years. Harvesting the palm oil fruits/fresh fruit bunches (FFB) usually starts in the second or third year after planting the tree (Corley and Tinker 2003; Singh 2006). The palms are productive from the age of 2–3 years up to the age of 25–30 years after planting while giving the highest yields in the first third to the middle of the life cycle. Corley and Tinker (2003) estimate an average age of palms when replanting at 25 years after planting. Azman and Noor (2002) calculate the optimal age of re-planting to be 25–26 years while Yusoff and Hansen (2007) estimate the age of palms when re-planting up to 30 years. In our estimation, we conservatively consider 25 years.

Oil palm cultivation implies several field work processes using fossil fuel such as planting of new palms, sowing of crop cover, fertiliser and pesticide application, harvesting and transportation to the oil mill nearby and finally after 25 years clearing and preparing the field for replanting (Schmidt 2007).

[1] The results of such analyses are can be expressed as the relation between the total GHG emissions and the energy content of different types of fuel, usually measured in carbon dioxide equivalents per megajoule (g CO_2 eq/MJ).

[2] The authors of the study sought to include data from the Joint Research Center that were used to develop the current values in the Directive. Requests for data were not returned.

The oil palm fruits are attached to bunches (FFB—fresh fruit bunches) of around 25 kg. Each FFB carries 1,500–2,000 single fruits (for oil palms 10–15 years old) and contains around 20 % oil, 25 % nuts (5 % kernels, 13 % fibre and 7 % shell) and 23 % empty fruit bunches. The kernels yield around 55 % oil and 8 % protein (Corley and Tinker 2003; Møller et al. 2000).

The palms are harvested year-round; each time only one FFB per oil palm is harvested. Harvesting is done manually, and the FFB are collected with a truck. Young palms are harvested with a chisel whereas old and tall palms are harvested with a long-handled sickle. As they are harvested only by manual labour, there is no fossil energy input to harvesting (Pleanjai et al. 2007). The fruit bunches are generally transported to the mill on the day of harvesting. When the palms are getting too unproductive, the palms are felled and usually replaced by new palms (Schmidt 2007).

2.2 Milling process

Although the specific milling process differs according to the products one wants to obtain, basically, the following steps are done in the oil mill. First, the sterilisation of the FFB is done batchwise in an autoclave with an internal temperature inside of about 120–130 °C to ensure the FFB is completely cooked. The steam condensate is the wastewater generated at this step. Second, the FFB are striped to separate the sterilised fruits from bunch stalks. This processing step generates the empty fruit bunches (EFB) that are put into the digester where they are mashed under steam-heated conditions. Often, the EFB is used as mulch in the oil palm plantation (Corley and Tinker 2003).[3] In a third step, the crude palm oil extraction, the homogenous oil mash from the digester, is pushed through a screw press and later passes through a vibrating screen, a hydrocyclone and decanters to remove fine solids and water. Centrifugal and vacuum driers are used to further purify the oil before sending it to a storage tank and later sold as CPO. The fibre and nuts from the screw press are usually separated in a cyclone. The fibre that passes out of the bottom of the cyclone can be used as boiler fuel from which ash (fertiliser) is produced after combustion. The nuts are cracked in a centrifugal cracker. After the cracking process, the entire palm kernels and shells are separated (e.g. by clay suspension). The separated shells from the kernels are used as boiler fuel. The kernels are further processed in order to extract the palm kernel oil (PKO).

The main environmental impact related to methane emissions from production of palm oil in the palm oil mill relates to the technology for treating palm oil mill effluent (POME). There are three main sources of POME in the palm oil mill: clarification waste water (60 % of total POME), steriliser condensate (36 % of total POME) and hydro cyclone waste water from nut and fibre separation (4 % of total POME) (Department of Environment 1999; Schmidt 2007). The most common treatment of POME is still an open anaerobic and aerobic ponds and later the use as land application and fertiliser (Lim et al. 1999). The alternative technology is the installing of digester tanks for biogas capturing and subsequent utilisation of biogas for electricity production. At the palm oil mill selected for his study, Schmidt (2007) describes how POME is digested anaerobically to yield biogas which is used in modified diesel engine with a 90-kW induction motor.

[3] EFB can also be used as substrate for mushroom cultivation and for the production of particle board (Pleanjai et al. 2007).

2.3 Refining process

The refining process includes neutralisation, bleaching and deodorisation of the oil. The output from the refinery is then refined palm oil (RefPO). In these steps of the production processes, some losses of oil take place.

The purpose of neutralisation (including degumming) is to remove lecithin and free fatty acids. The lecithin is removed by applying phosphoric acid (0.25 kg/t RefPO, UPRD 2004) in the degumming process. In the following, the content of free fatty acids is removed by applying sodium hydroxide (2.9 kg/t RefPO, UPRD 2004). When the sodium hydroxide reacts with the free fatty acids, the outcome is soap-water. Next, the mix of oil and soap-water is centrifuged in order to separate out the soap which is sold. The soap is sent through the soap stock splitting process were the outcomes are free fatty acids (used as fodder) and soap (sold to soap manufacturing) (Hansen 2006).

The bleaching process is applied in order to remove undesired coloured particles. In the bleaching process, the oil is brought in contact with Fuller's earth (bentonite), the most common used agent for filtering the oil, which absorbs the undesired particles (Schmidt 2007). In the bleaching process, oil is lost due to oil content of approximately 30 % oil in the used Fuller's earth (Singh 2006).

Finally, the oil is sent through the deodorisation process to remove undesired odoriferous or flavouring compounds. In the deodorisation process, minor amounts of different ancillaries are applied, for example, citric acid. Since these ancillaries constitute in-significant amounts (just a few gram per ton of RefPO), they are omitted in this study. About 0.1 % of the oil is lost in the deodorisation process (Hansen 2006).

2.4 Transport

The refined palm oil is then transported to final consumption for (co-generated) electricity production in Europe or further processing to FAME/biodiesel. The transportation stage includes the transport from the refinery to the port in the country of origin and the shipment of the refined palm oil to the EU.[4]

2.5 Esterification process

In order to convert refined palm oil into biodiesel (fatty acid methyl ester/FAME), which can be used by almost all conventional diesel engines in cars, usually a transesterification reaction comes into play. This process usually requires two to three stages with subsequent washing, drying and polishing of the reaction product. The refined, bleached and deodorised palm oil is thoroughly mixed with methanol and sodium hydroxide as a catalyst. The mixture is heated to the reaction temperature and fed to a reactor where the esterification reaction takes place. Glycerol formed in the reaction is separated from the methyl ester phase. Further conversion of the methyl ester takes place in a second and sometimes third reactor.

Once the reaction is complete, the major co-products, biodiesel and glycerin, are separated into two layers. The methanol is typically removed after the biodiesel and glycerin have been separated, to prevent the reaction from reversing itself. The methanol is cleaned and recycled back to the beginning of the process. Once separated from the glycerin, the

[4] Note that not just ready refined palm oil is exported but also significant amounts of crude palm oil (CPO).

Table 1 Top 10 producers of biodiesel

Country	Biodiesel production (thousand barrels per day)				
	2005	2006	2007	2008	2009
Germany	39.0	70.4	78.3	61.7	51.2
France	8.4	11.6	18.7	34.4	41.1
United States	5.9	16.3	32.0	44.1	32.9
Brazil	0.0	1.2	7.0	20.1	27.7
Italy	7.7	11.6	9.2	13.1	13.1
Thailand	0.4	0.4	1.2	7.7	10.5
China	0.8	4.0	6.0	8.0	8.0
Malaysia	0.0	1.1	2.5	4.5	5.7
South Korea	0.2	0.9	1.7	3.2	5.0
Lithuania	0.1	0.2	0.5	1.3	1.9
World	77.2	142.0	202.9	270.9	308.2

Source US Energy Information Administration (2011)

biodiesel goes through a clean-up or purification process to remove excess alcohol, residual catalyst and soaps.

Although a few facilities for esterification/biodiesel production have been established in the countries of origin in South-East Asia, the process of esterification usually takes place in facilities in the importing countries. The following Table 1 shows the 10 major producers of biodiesel sorted by output in 2009. Note that the first country that grows oil palms in a significant manner, Thailand, ranks 6th, far behind countries in Europe and America. The actual biodiesel production of Malaysia, as the second largest producer of crude palm oil in the world, significantly falls behind those on top of the list. Indonesia, the world's largest palm oil producer, does not even appear on this list.

Given the fact that the final stage of palm oil–based biodiesel is still usually done in the target country, the actual system boundary of production in the country of origin (e.g. South-East Asia) can be considered as the refinery or even the oil mill stage.

In order to do so, the very producer of FAME has to provide insights into the technology applied in the esterification process. As a matter of fact, adding artificial penalising factors[5] to the esterification process to get a default value is nonsense, even if the very FAME is produced in the country of origin. One should definitely refer to the current common technologies. Furthermore, new technologies available have dramatically reduced the energy intensity of the transformation process of vegetable oils into FAME, not to mention Next Generation Biomass-to-Liquid (NExBTL-biodiesel) and Hydrotreating. This has to be considered from case to case while assessing the GHG emissions of the very biofuel produced.

3 Methodology

In order to calculate the GHG impact of palm oil, a life cycle analysis including all activities associated with the production, transformation, transport and use of the

[5] The European Union (EU) (2009) Directive calculates with an average penalising factor of 1.4.

respective biofuel has to be conducted. The methodology of the calculation scheme is laid down in part C Annex V of the Directive 2009/28/EC and in Annex IV.C of Directive 2009/30/EC (land use chance). As in the EU-Directive (European Union (EU) 2009) Annex V(C), GHG emissions reductions are calculated as follows:

$$\text{SAVING} = (E_F - E_B)/E_F;$$

where E_B is the total emission from the respective biofuel and E_F is the total emissions from fossil biodiesel. Greenhouse gas emissions from the production and transport of fuels, biofuels and bioliquids shall be calculated as:

$$E_B = e_{ec} + e_l + e_p + e_{td} + e_u + e_{sca} + e_{ccs} + e_{ccr} + e_{ee}$$

where E_B, total emissions from the use of the fuel; e_{ec}, emissions from the extraction or cultivation of raw materials; e_l, annualised emissions from carbon stock changes caused by direct land use change; e_p, emissions from processing; e_{td}, emissions from transport and distribution; e_u, emissions from the fuel in use; e_{sca}, emission saving from soil carbon accumulation via improved agricultural management; e_{ccs}, emission saving from carbon capture and geological storage; e_{ccr}, emission saving from carbon capture and replacement; and $e_{ee,}$ emission saving from excess electricity from cogeneration.

The aim of this paper is to calculate realistic and transparent scenario-based CO_2-emission values for the GHG emission savings of palm oil fuel compared with fuel from crude oil. Using the same basic calculation scheme, we derive a more realistic overall GHG emissions saving value for palm oil diesel by using current input and output data of biofuel production (e.g. in South-East Asia) documenting every single step in detail. We calculate different scenarios in which reliable data on the production conditions (and the regarding emissions values during the production chain) of palm oil diesel are used.

As shown in the previous chapter, the production of palm oil is divided into five stages: agricultural stage, oil mill stage, re-finery stage, transport stage and esterification stage. The transport stage only includes transport of oil from the refinery to final use which is assumed to be in Europe represented by Port Rotterdam. Other transport processes are included in the other life cycle stages.

Overhead (operation of buildings, administration, marketing, etc.) and capital goods (building, machinery and means of transportation) are not considered in our LCA, as—according to the EU-Directive (EU 2009, Annex V, C Methodology)—emissions from the manufacture of machinery and equipment shall not be taken into account.

The determination of the system boundaries of the oil mill stage and refinery stage is based on the methodology presented in Schmidt and Weidema (2008), and the determination of the system boundaries relating the agricultural stage is based on the methodology presented in Schmidt (2008).

We use a conservative baseline model to calculate GHG emissions for every step of the palm diesel production chain based on the background data provided by the latest available version of the JEC database (see Appendix, Table 8).[6] Furthermore, for the very inputs and outputs of the production process, we use also conservative values based on the average of the values found in reliable scientific studies.

We use the calculation tool provided by IFEU (2010) based on the Intelligent Energy Europe (IEE) project BioGrace (2010). This tool is engineered to produce greenhouse gas (GHG) calculations using the methodology as given in the Directives 2009/28/EC

[6] Background data are taken from the JEC (2011) E3-database (version 31-7-2008).

(Renewable Energy Directive) and 2009/30/EC (Fuel Quality Directive). In contrast to the EU-Directive (European Union (EU) 2009) as well as all other studies, we do not use unaudited assumptions but rely only on exact measured and proven primary data instead. All data are well documented in our study. Thus, we provide a full transparency by indicating all input and output data, assumptions and background data.

There is some evidence that a considerable share of the oil palm expansion has and is taking place on land released from other crops (Corley and Tinker 2003; Henson 2004; Teoh 2000). In the past, oil palm in Malaysia has largely been planted on land released from rubber, coconut and cocoa (Henson 2004). This could be confirmed with data obtained from FAOSTAT (2006) for Malaysia where the planted area of rubber, cocoa and coconuts has been decreasing from around the year 1990 to the year 2005 while the planted area of oil palm has been increasing at the same rate during the same period of time.

However, looking at Malaysia and Indonesia in sum, there is a general increase in the cultivated area of rubber and coconut, and only a small decrease in the cultivated area of cocoa is identified from 1994 to 1999 (FAOSTAT 2006). Thus, it seems that there is no large-scale displacement of other crops by oil palm plantations (indirect land use change) but obviously a transformation of nonagricultural land into oil palm cultivation instead.

To asses the emissions related to direct land use change, the question then is what kind of land is transformed. Most NGO's claim that land transformation towards oil palms is related to clearing of primary forest, see for example, Casson (2003), Frese et al. (2006) and Wakker (2004). However, oil palm plantations are "almost always established on already disturbed land" (Schmidt 2007, based on studies of Bek-Nielsen 2006; Glastra et al. 2002; ProForest 2003).

Disturbed land may be either cleared forest (alang–alang grassland), secondary forest, or abandoned agricultural land. Schmidt (2007) states that it is not possible to estimate the composition of land types transformed into oil palm exactly. However, he assumes that 50 % takes place by transformation of degraded/secondary forest and the other 50 % of oil palm expansions takes place by transformation of grassland. If oil palm is planted directly on transformed primary forest, the transformation from primary to degraded forest is related to logging in the fist instance since change in demand for timber is the main driving force of logging (Schmidt 2007). Analysing data from FAO (2005), FAOSTAT (2006), and Pagiola (2000), Schmidt (2007) concludes that the annual deforestation in Malaysia and Indonesia is significantly larger than the increase in agricultural area, also when looking at degradation of primary forest only.

This comparison suggests that it is unlikely that oil palm is the main driver of logging primary forest. Pehnelt and Vietze (2009) consider that land might have been initially deforested for other reasons and then finally be planted with oil palm. Using these formerly degraded and abandoned agricultural lands to grow native perennials like oil palms for biofuel production is economically and ecologically efficient as this could spare the destruction of native ecosystems. Moreover, this measure reduces GHG emissions as carbon being stored in the soil and the growing palm (Fargione et al. 2008; Field et al. 2008; Tilman et al. 2006). According to the German Advisory Council on Global Change (2008), in such a situation a major climate change mitigation effect can be achieved at very low cost.

Because of these uncertainties regarding the reasons and effects of land use change, we do not consider this problem explicitly in the current paper. As our aim is a realistic, reliable and scientifically founded approach, we focus our research on GHG emissions related to plantation, processing and transport of palm biodiesel, as only these steps are considered to calculate the EU typical and default value. Furthermore, the issue of land use

Table 2 FFB yields in Malaysia and Indonesia

Region	Average yield 1990–2005 (linear regression 1990–2005 by Schmidt 2007) (t/ha)	Yield 2003 (t/ha)	Yield 2003 (t/ha)	Yield 2003 (t/ha)
Malaysia	19.84	20.48	20.49	20.90
Indonesia	17.95	17.30	18.20	17.85
Malaysia and Indonesia	18.87	18.95	19.36	19.38

Source Schmidt (2007, p. 87)

change (as well as biodiversity) is addressed by the other criteria given by RED and is considered separately from the very GHG emissions saving potential.[7]

3.1 Plantation stage

As further explained in Sect. 2.1, we conservatively consider an oil palm life cycle of 25 years in our estimation.

Our data are based on data on cultivation practices in Malaysia, currently the second largest producer of palm oil. Since oil palm is a perennial, three different stages must be considered: (i) nursery, (ii) immature plantation and (iii) mature plantation. The interventions from oil palm cultivation are applied as a weighted average of the immature and mature plantation. Schmidt (2007) regarded the seed production and nursery as insignificant for oil palm cultivation due to the lifetime of oil palms of 25 years. The immature stage is regarded as the first 2 years after planting. After that, the palms are supposed to provide yields (FFB) for 23 years. The yields of FFB applied in our models are based on the average yields in Malaysia and Indonesia as obtained from FAOSTAT (2006). We rely on the calculated linear regressions of yields from 1990 to 2005 by Schmidt (2007) of averaging 18.87 t FFB per ha. In further scenarios, we use more recent output figures (see Table 2).

For several field work processes of oil palm cultivation (e.g. planting of new palms, sowing of crop cover, fertiliser and pesticide application, harvesting and transportation), fossil fuel is used. For that, we use the diesel consumption in machinery in the plantation as a total value including all field work processes per ha per year. The applied energy use is 58.19 l per ha per year, the average of Singh (2006), Unilever (1990) and Yusoff and Hansen (2007).

The major emission source of plantation relates to fertilisers. The fertiliser uses applied in this study are shown in Table 3. We adopt the average of five different sources on the

[7] Nevertheless, expecting an increasing demand in palm oil, the question is where the new plantations could be established. According to Garrity et al. (1997) and Corley (2006) large areas of alang–alang grassland is available for expanding the agricultural area in Indonesia. Garrity et al. (1997) estimate the area of alang–alang grass land in Malaysia as 1,000–5,000 km^2, i.e. 0.3–1.5 % of the total area, while the area of grassland available for agricultural expansion in Indonesia is 75,000–130,300 km^2, i.e. 4–7 % of the total area. Unlike to the clearing of primary forests, this kind of land use change is beneficial regarding the CO_2 emissions balance of palm oil. Schmidt (2007) analyses CO_2 emissions relating from land use chance from alang–alang grassland to oil palm in Malaysia and Indonesia. By using data on the respective carbon and nitrogen stock from Billore et al. (1995), IPCC (2003) and Henson (2004) he estimate an CO_2 emission from land use chance (alang–alang grassland to oil palm) of -33 t CO_2 eq per ha. Related to the average life time of an oil palm cultivation of 25 years this equates to annually GHG emissions of -1.32 t CO_2 eq from land use chance.

Table 3 Fertiliser use oil palm plantation

Fertiliser	N (kg N/ha)	P (kg P_2O_5/ha)	K (kg K_2O/ha)	Ca (kg CaO/ha)	Source
Applied fertiliser in oil palm plantations					
United Plantations 2005	136	77	297	0	United Plantations Berhad (2006)
Malaysia, average	96	28	172	0	Yusoff and Hansen (2007)
Malaysia, costal soils	124	128	256	0	Subranamiam (2006a)
Malaysia, average 2001	100	45	205	0	IFA et al. (2002)
Malaysia, average 2002	76	86	119	0	FAO (2004)
Malaysia, immature	90	35	140	0	Henson (2004)
Average value (mature)	106	73	210	0	Average of 1, 2, 3, 4 and 5
Average value (immature)	90	35	140	0	The value given in 6
Applied value (2 years immature; 23 years mature)	105	70	204	0	Average value
Theoretical figures					
Recommended application (by MPOB)	128	144	200	–	FAO (2004)
Nutrient demand, 10-year-old palms	114	32	180	–	Corley and Tinker (2003)
Nutrient demand, 15-year-old palms	182	56	315	–	Corley and Tinker (2003)

Source Schmidt (2007, p. 91)

fertiliser use in mature oil palm plantations (FAO 2004; IFA et al. 2002, p. 13; Subranamiam 2006a; United Plantations Berhad (UPB) 2006, p. 110, 123, 129; Yusoff and Hansen 2007) and one data source for immature oil palms (Henson 2004, p. 36) in Malaysia. According to the oil palm life cycle, the total amounts of applied nutrients in fertiliser in oil palm plantations are calculated as the average of 2 years immature and 23 years mature palms.

Thus, the applied uses are 105 kg N/ha, 31 kg P/ha (70 kg P_2O_5/ha), 170 kg K/ha (204 kg K_2O/ha) and 21 kg Mg/ha (35 kg MgO/ha). We use the same calculation methodology as in RED (European Union (EU) 2009) and—therefore—the RED values for N_2O field emissions (8,264.84 gCO_2 eq per kg N-fertiliser). Hence, the direct N_2O field emissions of the plantation of N-fertilisers are included in the emission calculation related to the input of N-fertiliser. It is important to note that the nutrient demand for oil palm is the total demand that may be met by inputs of artificial fertilisers, biomass residuals (pruned fronds, EFB and POME), decomposition from the atmosphere and possible decrease in the soil nitrogen pool. Therefore, the nutrient demand cannot be expected as a stand alone guideline for the application of artificial fertiliser (Schmidt 2007).

For the use of pesticides, we obtain data by Singh (2006). The applied active ingredient (a.i.) of pesticides is 2.7 kg per ha per year (2.4 kg a.i. glyphosate/ha, 0.31 kg a.i. cypermethrin/ha, 0.013 kg a.i. fungicides/ha and 0.00021 kg a.i. warfarin/ha), the average of 2 years immature and 23 years mature oil palm. Often, the use of pesticides is reduced by an integrated pest management programme. That includes the planting of beneficial flowering plants that attract parasites and predators of the common pests of the oil palm

(Arulandoo 2006; Fee and Sharma 1999). Rats, another serious pest, which damage the seedlings in the nursery, immature palms and eat the fruits, are controlled by barn owls that are attracted by setting up nesting boxes (Fee and Sharma 1999).

3.2 Oil mill stage

The values for the production process of the oil mill stage are mainly based on Singh (2006), Subranamiam (2006a) and general literature on oil palm processing: Department of Environment (1999), Schmidt (2007) and Singh et al. (1999).

In our estimation scenarios, the entire palm kernels are treated with the specific heating value as by-product. Alternatively, we consider in another baseline scenario that the output of entire palm kernels in the milling stage is further processed in the oil mill to palm kernel oil (PKO) and palm kernel meal (PKM). We account for the electricity needed additionally. Although the values for the GHG savings are smaller (as we count only the heating value of by-products), two high value co-products would be produced. Cold-pressed PKO is used as a high quality edible oil and palm kernel meal as food for livestock.

It appears from the description of the production process that the palm oil mill has several product outputs. The production of crude palm oil (CPO) of 199.8 kg per t FFB and kernel of 53.2 kg per t FFB is determined as the Malaysian average in 2003–2005 given in MPOB (2005) and MPOB (2006). We apply values according Malaysian national figures as the average of 1996 (Singh 1999) and 2002 (Ma et al. 2004) figures on the product flows of fibre (130.0 kg/t FFB), shell (70.0 kg/t FFB), EFB (225.0 kg/t FFB) and POME (672.5 kg/t FFB) per tonne of processed FFB.

The main environmental impact related to the production of palm oil in the palm oil mill regards to the technology for treating palm oil mill effluent (POME). There are three main sources of POME in the palm oil mill: clarification waste water (60 % of total POME), steriliser condensate (36 % of total POME), and hydro cyclone waste water from nut and fibre separation (4 % of total POME) (Department of Environment 1999; Schmidt 2007). The most common technology for treating POME is open anaerobic and aerobic ponds and later the use as land application and fertiliser (Lim et al. 1999). Therefore, this treatment is applied in our baseline scenario. However, this causes high emission levels of the green house gas methane. The alternative technology is the installing of digester tanks for biogas capturing and subsequent utilisation of biogas for electricity production. As value for the methane emissions from POME, we apply 1,093.59 g CO_2 eq per kg CPO. We calculate this value according to average POME output of 672.5 g POME per kg FFB (Ma et al. 2004; Singh 1999) and CH_4 emissions of 13.0 g per kg POME (Ma et al. 2004; Yacob et al. 2006).[8] The converted value is calculated from production yield of 0.1998 t CPO per t FFB and the methane emissions of POME of 8.74 g per kg FFB and the methane GWP of 25 CO_2 eq.

The energy supply to the oil mill includes electricity and steam. Most, if not all, palm oil mills are self-sufficient in electricity and heat (Henson 2004, p. 30). Normally, fibre and shells are burned for energy purposes (Department of Environment 1999; Henson 2004; Subranamiam et al. 2005; Weng 1999). Schmidt (2007) analyses the required input data of

[8] The methane content of biogas is 65 % (Ma et al. 2004). Thus, the methane emission could be calculated as 18.2 m^3 per t POME. With a density of methane at 0.717 g per litre (Andersen et al. 1981, p. 119), the CH_4 emission is 13.0 kg per t POME. Yacob et al. (2006) have measured the methane emission from a pond system over a period of 12 months. The average methane emission is 13.1 kg CH_4/t POME. This is in good accordance with the figures provided in Ma et al. (2004).

energy (steam and electricity) and heating values of fibre and shell of Chavalparit et al. (2006), Husain et al. (2003), Singh and Thorairaj (2006), Subranamiam et al. (2005), and Weng (1999). He concludes that all of the fibre and shell are used as boiler fuel. Thus, 130.0 kg fibre and 70.0 kg shell are burned per tonne of FFB input. Fibre and shell have calorific values 19.1 MJ per kg and 20.1 MJ per kg (dry matter basis), respectively (Subranamiam et al. 2004). With average moisture content of fibre (40 %) and shell (10 %) (values given in Ma et al. 2004; Singh 1999; Yusoff 2006; Yusof and Weng 2004), the calorific value of the fuel composition of 65 % fibre and 35 % shell can be determined as 13.8 MJ per kg. Hence, the theoretical energy input is 2,763 MJ per t FFB.

Husain et al. (2003) surveyed seven palm oil mills where utilisation factors averaging at 65.6 %. The average heat to power ratio is 17.9 %. Thus, the total heat and power production per t FFB is 1,811 MJ distributed on 1,708 MJ steam and 104 MJ electricity. The figures on steam and electricity production per t FFB could be confirmed by Singh and Thorairaj (2006). According to Singh and Thorairaj (2006) and Subranamiam et al. (2005), the steam requirement for processing of 1 tonne FFB is 1,691 MJ or 469.7 kWh. It is usual that excess steam is released to the atmosphere (Kandiah et al. 1992; Subranamiam 2006a). Therefore, we assume that the difference between the required steam (469.7 kWh) and the produced steam (474.4 kWh) is released to the atmosphere.

The electricity recovered from the turbine, that is, 104 MJ/t FFB or 28.9 kWh per t FFB, exceeds the requirement for processing the FFB. The required electricity for processing 1 t FFB varies between 14.5 kWh (Chavalparit et al. 2006) through 17.7 kWh (Yusoff and Hansen 2007) to 18–22 kWh (Singh and Thorairaj 2006) and 20 kWh (Ma et al. 2004).

We assume an average requirement of 20 kWh per t FFB. Thus, there is approximately 30 % electricity in excess, that is, 8.9 kWh per t FFB. If palm oil mills are not connected to the national grid, the excess electricity displaces electricity from the grid indirectly, as it is used locally on the estate in administration and residence buildings for the workers and there families and sometimes in a refinery if the estate has its own refinery plant. Since these buildings are connected to the national grid or to local generators, the excess electricity displaces electricity delivered from the grid directly. In addition to the input of fibre and shell, the power central uses fossil fuel for start-ups of the boiler in the power central. According to Subranamiam et al. (2005), oil mills use 0.37 litre of diesel per t FFB.

Palm kernel oil and palm kernel cake are extracted from the kernels in a mechanical pressing process to produce high valued edible palm oil (MPOB 2006; Singh 2006). According to Subranamiam (2006a), mechanical pressing in Malaysia is done using a double pressing method without pre-heating.

The inventory is mainly provided by Subranamiam (2006a, b). The palm kernel oil mill processes the kernels from the palm oil mill into palm kernel oil (PKO) and palm kernel meal (PKM). The product flow (Bockisch 1998) of PKO, PKC and processed entire kernels is based on average figures from 2002/2003 to 2003/2004 given in Oil World (2005). To produce 1 t PKO and 1.161 t PKM, 2.228 t entire palm kernels are processed.

In this analysis, we apply an energy use of 267.2 kWh per t PKO in Malaysian palm kernel oil mills given in Subranamiam (2006b). This is allocated with the excess electricity of the CPO milling stage in our calculations. All input values of PKO milling are converted to the input of 10,000 t FFB in the CPO milling stage according the respective output of entire palm kernels in the different scenarios.

Transport of FFB to the oil mill is included in our values of diesel use in the plantation stage. All transports of FFB takes place in the plantation since oil mills are situated in or very close to the plantation (Schmidt 2007).

3.3 Refinery stage

In the refining process (e.g. neutralisation, bleaching and deodorisation) of palm oil, nearly non additional chemicals are used. As (the small amounts of) phosphoric acid and sodium hydroxide are only used in the production of the by-products animal food and soap, according to IFEU (2010), we neglect these chemicals as input factors. In the steps of the production processes to refined palm oil (RefPO), some losses of oil take place. The loss in the neutralisation process mainly includes the separated free fatty acids. Corresponding to Kang (2006), CPO has free fatty acid content of between 3 % and 5 %. Thus, Schmidt (2007) assumes that CPO sent to refining has free fatty acid content at 4.2 % and the loss in the neutralisation process is calculated at 4.2 % similarly. Since the use of bleaching earth is 4.53 kg per t RefPO (UPRD 2004), the loss of oil in the bleaching process can be calculated at about 0.2 %.

The used energy for all production steps of the refinery stage is calculated by Schmidt (2007). He assumes a use of 35 kWh per t RefPO electricity from the grid and heat input of 328 MJ per t RefPO which is provided by burning 9 litres of diesel per t RefPO.

3.4 Transportation stage

The refined palm oil produced in South-East Asia is supposed to be transported in a diesel operated truck for about 200 km on average to a port (Schmidt 2007). From there, it is transported in an oceanic tanker operated with HFO. The average distance between major ports in South-East Asia and Europe has been conservatively calculated to be 14,975 km (PortWorld Distances 2011).[9]

In alternative scenarios, we calculate with the EU default value of 135 g CO_2eg per kg RefPO provided by JEC (2011) E3-database (version 31-7-2008).

3.5 Esterification

Based on the standard methodology proposed by the EU (2009) (Directives 2009/28/EC and 2009/30/EC), we have calculated the GHG emissions that can be expected in the transesterification process in which methanol is combined with the refined palm oil in order to derive palm oil methylester. During this process, glycerol evolves as a by-product. This by-product can for instance to be used to produce soap or other materials. Although the economic value of glycerol might be higher than its calorific value, we only consider the energy content of this by-product in calculating the GHG emissions of the whole process.[10]

In the calculations documented in the following Table 4 we, again, use conservative values on the efficiency of the esterification process based on common technologies using values for energy consumption and chemical inputs on the upper end of the range that can be found in recent publications.

Taking the energy content of the by-product glycerol into account, we end up with a total net GHG emission of about 10.29 g CO_2 eq/MJ FAME.

Alternatively, we use a second scenario of the esterification process in some of our calculations. The GHG emissions of more sophisticated current technologies are supposed to be

[9] The distance represents the distance from Port Kelang in Malaysia to the port in Rotterdam (The Netherlands).

[10] The by-product glycerol provides a GHG emissions credit.

Table 4 Esterification process—background data GHG emissions calculations

	Value		Unit	
Yield				
FAME	0.9965		MJ FAME/MJ RefPO	
By-product refined glycerol	105.00		kg/t FAME	
			GHG emissions	
			Value	Unit
Energy consumption				
Electricity	0.0041	MJ/MJ FAME	0.5213	g CO_2 eq/MJ FAME
Steam (from NG boiler)	0.0760	MJ/MJ FAME		
NG Boiler				
CH_4 and N_2O emissions from NG boiler			0.0304	g CO_2 eq/MJ FAME
Natural gas input/MJ steam	1.1111	MJ/MJ Steam		
Natural gas	0.0844	MJ/MJ FAME	5.7408	g CO_2 eq/MJ FAME
Electricity input/MJ steam	0.0200	MJ/MJ Steam		
Electricity	0.0014	MJ/MJ FAME	0.1949	g CO_2 eq/MJ FAME
Chemicals				
Phosphoric acid (H_3PO_4)	0.05000	g/MJ FAME	0.1515	g CO_2 eq/MJ FAME
Hydrochloric acid (HCl)	0.55000	g/MJ FAME	0.4142	g CO_2 eq/MJ FAME
Sodium carbonate (Na_2CO_3)	0.06800	g/MJ FAME	0.0818	g CO_2 eq/MJ FAME
Sodium hydroxide (NaOH)	0.18500	g/MJ FAME	0.0872	g CO_2 eq/MJ FAME
Methanol	0.05900	MJ/MJ FAME	5.9087	g CO_2 eq/MJ FAME
Total gross GHG emissions			13.1309	g CO_2 eq/MJ FAME
By-Product Glycerol			2.8452	g CO_2 eq/MJ FAME
Total net GHG emissions			10.2857	g CO_2 eq/MJ FAME

far below the overall emissions of older procedures.[11] This is the case for both this esterification process and the production of methanol which accounts for most of the overall GHG emissions associated with the whole process. New technologies include bio-methanol, synth-ethanol as well as lower temperatures and lower energy input in the very esterification process.[12] A reliable and reasonable figure for GHG emissions of current technologies in vegetable oil esterification can be found in Weindorf (2008). Although the GHG emissions credit of the by-product glycerol—which reduces the total GHG emissions value—supposed in Weindorf (2008) is quite small (1.2 g CO_2 eq/MJ) and well below the calculations shown in the table above, we use the value of 7.1 g CO_2/MJ FAME in our alternative scenarios.

3.6 Reference value

The reference value for the GHG emission savings, the average CO_2 emission resulting from the combust of fossil diesel, is problematic, since the CO_2 emissions from the

[11] For some technical details of the esterification and purification process see Chongkhong et al. (2007) and Suppalakpanya et al. (2010).

[12] Note that we do not take into account even more sophisticated technologies such as ethyl transesterification, co-processing or hydrogenisation which offer much lower GHG emissions than current methyl esterification practices.

Table 5 GHG emission from production, transport and distribution of fossil diesel (without direct emissions from combustion)

Source	Silva et al. (2006)	CONCAWE et al. (2006)	GM et al. (2002)
g CO_2 eq/MJ diesel	14.2	14.2	10.2

extraction of these fuels have to be taken into account and these emissions vary depending on the very process. The European Union (EU) (2009) sets the reference value for GHG emissions from fossil fuel at 83.8 g CO_2 eq/MJ.

Table 5 summarises the emissions generated in the production phase of European diesel, as calculated by recent studies.

Given these figures, the total emissions in the life cycle of fossil diesel vary between 83.3 and 87.3 g CO_2 eq/MJ (73.1 g CO_2 eq/MJ for direct combustion). The EU reference value for GHG emissions is close to the lower bound of this range and therefore rather underestimating the carbon savings of biofuels (Pehnelt and Vietze 2009). That is why we are using two different reference values in our models.

It should be noticed that the values given above do not take into account the exhaustibility of crude oil reserves. Future extraction of fossil oil is likely to cause substantially higher GHG emissions than the EU reference value. For example, the extraction of oil from bituminous sands, widely spread especially in Canada, requires large quantities of steam, and the fuel produced using these resources is expected to cause about 50 % more GHG emissions compared with the extraction and use of conventional crude oil. Similarly, with almost a third of the coal's chemical energy loss in terms of waste heat in the conversion process, the coal-to-liquid process technology, which is seen as an alternative to conventional oil resources, is also less efficient (Pehnelt and Vietze 2009). Furthermore, the future extraction and use of the remaining conventional oil reserves will produce higher GHG emissions than today, owing to the smaller size and geographic inaccessibility of the remaining productive fields (Cockerill and Martin 2008).

Additionally, in all scenarios, we refer to a third reference value for palm oil used for electricity production. We use the value of 91 g CO_2 eq/MJ for electricity production from fossil oil regarding and the 'Guidance on Sustainable Biomass Production' (BiokraftNachV) published by the German Federal Agency for Food and Agriculture (BLE 2009) and the EU-Directive 2009/28/EC (European Union (EU) 2009). As the generation of electricity operates with refined plant oil (without transesterification), we calculate the CO_2 emissions savings of electricity production after the refinery stage.

3.7 Allocation of by-products

Like many other production processes, biofuel production is a multi-input/multi-output product system. Therefore, to correctly evaluate the impacts of biofuels, co-products need to be taken into account as well. Allocation of by-products is the method by which input energy and material flows as well as output emissions are distributed among the product and co-products. There are quite a few methodologies of integrating the allocation of co-products into LCA, among others mass allocation, economic allocation, energy or exergy allocation and substation method. The very method applied may have considerable impacts on the final results and is also an area of extensive debates and discrepancies among different LCA studies (Menichetti and Otto 2009).[13]

[13] See for instance Weidema (2001).

In order to assess the effects of by-products, one could choose a mass-based allocation scheme, methods that take the energy content into account or an economic allocation. The latter, economic allocation, takes the actual economic value of the co-products into account and therefore provides an (potential) income perspective. Such an assessment seems to be the preferable one for LCA since it reflects the actual market conditions more properly than other methods. However, because prices may fluctuate quite rapidly, economic allocation methods significantly increase the volatility of results and therefore their uncertainty. Ideally, this approach would require analysts to re-conduct an LCA study several times and adjust the results accordingly. However, this is very difficult for regulatory implementation purposes (Menichetti and Otto 2009). This is likely the reason that most LCA studies on biofuels focus instead on other allocation methods. The most common allocation method is the energy allocation which takes the energy content of the by-products into account. This is indeed a pragmatic approach since the calorific value of certain by-products can be measured relatively easily, with the results usually within a very narrow range. However, a combination of energy content allocation and economic allocation still seems to be more appropriate to assess the overall impact of biofuels over their lifetime.[14]

Because we want to be as close as much to the current methods of calculating GHG emissions saving potentials used for regulatory purposes, for example, the methods applied by the European Union (EU) (2009), we also use—according to IFEU (2010) and BioGrace (2010)—an allocation scheme based on the energy content of the by-products. This allocation method is indeed not very generous to palm oil–based biodiesel, especially if high value by-products such as palm kernel oil are part of the production chain.

4 Results

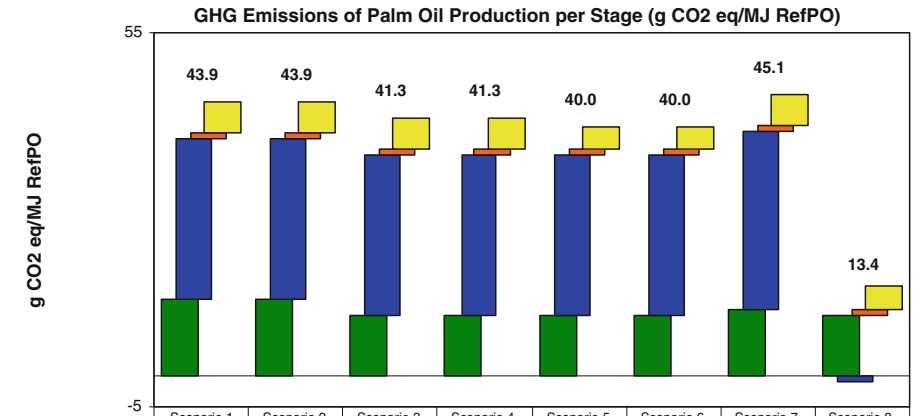
By using the above mentioned values, we ran estimations on the GHG emissions saving potential of palm biodiesel in different scenarios. In all scenarios, we derive the GHG emissions of every step of the palm biodiesel production chain. Moreover, we present three values for the overall GHG emissions saving potential regarding the respective fossil fuel comparator.

The first value shows the GHG emissions savings of palm oil used for electricity production regarding RED (EU 2009) and the 'Guidance on Sustainable Biomass Production' (Biokraft-NachV) published by the German Federal Agency for Food and Agriculture (BLE) and is the technical aspect of chapter IX 'Concrete calculation of greenhouse gas reductions' (BLE 2009). The second value displays the saving potential compared with the value of fossil oil as stated by the EU-Directive (EU 2009). Additionally we estimate the GHG emissions saving compared with current LCA of fossil fuel emissions as applied by CONCAWE et al. (2006), and Silva et al. (2006).

Figure 1 shows the GHG emissions of every single step of the production of refined palm oil (g CO_2 eq/MJ RefPO), namely plantation, oil mill, refinery and transport from South-East Asia to Europe.[15]

[14] Note that mass allocation turns out to be much more generous to biofuels than other methods (Menichetti and Otto 2009). Furthermore, using economic allocation methods, the results are more in favour of palm oil biodiesel than for other oil seeds such as rapeseed.

[15] Note that the transportation of FFB and other pre-products in the country of origin is considered in the plantation step in most scenarios. See the detailed tables in the Appendix.



	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8
transport (to EU)	4.95	4.95	4.95	4.95	3.65	3.65	4.95	3.65
refinery	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93
oil mill	25.77	25.77	25.68	25.68	25.68	25.68	28.61	-0.89
plantation	12.23	12.23	9.73	9.73	9.73	9.73	10.56	9.73
total GHG emissions	43.88	43.88	41.30	41.30	40.00	40.00	45.05	13.43

Fig. 1 GHG emissions of palm oil production per stage

The GHG emissions in connection with the cultivation process (plantation) account for about 9.7–12.2 g CO_2 eq per MJ refined palm oil, dependent on the very conditions such as fertiliser use, etc.[16] The implementation of specification of land use or land use change might significantly affect these calculations, ranging from huge GHG credits in the case of formerly degraded or marginal land to moderate GHG credits or GHG emissions close to zero in the case of formerly agricultural area in use to moderate additional GHG emissions in the case of secondary rainforest and an initial carbon debt in the case of primary rainforest on peat land.

However, as explained in the previous chapters, we do not cover land use change explicitly in our calculations since this issue is subject to separate criteria in the Renewable Energy Directive (European Union (EU) 2009).

GHG emissions associated with the refinery process are marginal. The GHG emissions of the transport of the refined palm oil to the importing country (EU) are also comparably small even when very conservative figures are applied higher than the JEC standard value.

If the methane emissions in the milling process are not captured (scenarios 1–7), the oil mill process accounts for the highest GHG emissions because of the highly GHG relevant emissions of methane in POME. The results clearly indicate that methane capture is the most desirable technology since GHG emissions could be dramatically reduced if a full methane capture in the milling process is applied. However, in most small-scale oil mills, this technology is not available yet and investments in this technology might be too expensive for small operators. However, efforts to introduce this technology sector wide are already under way (see Sect. 2.1).

[16] We calculate the GHG emissions of every single step per MJ refined palm oil. The efficiency of the milling and refining process indeed has an impact on the very output and therefore the figures calculated for pre-processing steps. In order to reduce the range of our results, we are using a rather narrow and conservative bandwidth of the efficiency of the full production process.

Overall, the GHG emissions of the production of refined palm oil are supposed to range from about 40 g CO_2 eq per megajoule (scenario 5 and 6) to about 45 g CO_2 eq per megajoule (scenario 7).

For all of our scenarios, we calculate the GHG emission saving potentials of refined palm oil as an input in power plants (electricity production) as well as the GHG emissions saving potentials of palm oil–based biodiesel (FAME) produced by using common but not highly sophisticated esterification technologies. All relevant data and results are documented in detail in the Appendix of the paper.

In scenario 1 (see Table 6), we use the average of the range of values that can be found in studies on palm oil (see again the paragraphs on the methodology in this paper). In scenario 1, the energy content of entire palm kernels is considered as a co-product, regardless of the further processing of these palm kernels which usually provides high value products.[17] For esterification, the value on GHG emission (Weindorf 2008) is applied in scenario 1.

The results of scenario 1 (for an overview of the scenario assumptions see Table 7) indicate GHG emissions savings of palm oil biodiesel clearly beyond the EU's 35 % threshold. Namely, the GHG emission saving potential of refined palm oil used for electricity production in power plants is 52 % compared with fossil electricity production (see Fig. 2).

The GHG emissions saving potential of biodiesel used in vehicle engines compared with fossil fuel ranges between 38.5 and 41.0 %, dependent on the very fossil comparator used (see the two charts of Fig. 3).

In scenario 2 (Table 9), we apply a value for GHG emissions in the esterification process conducted by calculations based on conservative values. The same data for plantation, oil mill, refinery and transport as in Scenario 1 are used. Because of the higher GHG emissions of the esterification process in this scenario, the GHG saving values are slightly inferior to scenario 1.

Only in the worst case scenario with the low fossil fuel comparator I, the GHG emission saving fails to reach the 35 % threshold by just a few tenths of a percentage point (see two charts of Fig. 3).

An estimation of the most current data on the production process of palm biodiesel is used in scenario 3 (Table 10). In general, an increase in the output and a decrease in the input figures because of improvements in the entire production chain have been observed in recent years. Current comments and data indicate that the output per hectare might be even higher with new varieties of oil palm and current cultivation technologies. However, since the information could not be verified through the published sources, we do not use these figures in our scenarios. In order to get closer to current production patterns, we use the most current values on plantation (fertiliser and pesticide input, output of FFB), the oil mill stage (output, achievements in POME treatment), and esterification (energy input) available in reliable sources in scenario 3. For the refinery and transport stage, we could not verify values other then those used in our baseline scenario. The emission saving values reflect the observed improvements along the production chain: With 55.0 % saving compared with conventional energy production and 41.6 % (comparator I) and 44.0 % (comparator II) saving compared with fossil diesel, the EU target is easily reached.

[17] It shall be mentioned again that an economic or mass allocation of by-products would produce results more beneficial to palm oil biodiesel than the energy content allocation method used here.

Table 6 Scenario 1—Entire PK, esterification latest values

	Value	Unit	Source
Plantation			
Output			
Yield FFB per ha	18,870	kg FFB per ha per year	FAOSTAT (2006)
Input			
N-fertiliser	105	kg N per ha per year	Yusoff and Hansen (2007), Subranamiam (2006a), UPB (2006), FAO (2004), Henson (2004), IFA et al. (2002)
P_2O_5-fertiliser	70	kg P_2O_5 per ha per year	Yusoff and Hansen (2007), Subranamiam (2006a), UPB (2006), FAO (2004), Henson (2004), IFA et al. (2002)
K_2O-fertiliser	204	kg K_2O per ha per year	Yusoff and Hansen (2007), Subranamiam (2006a), UPB (2006), FAO (2004), Henson (2004), IFA et al. (2002)
CaO-fertiliser	0	kg CaO per ha per year	Yusoff and Hansen (2007), Subranamiam (2006a), UPB (2006), FAO (2004), Henson (2004), IFA et al. (2002)
Pesticides	2.73	kg active ingredient per ha per year	Singh (2006)
Diesel (for all activities and transport)	58.2	l per ha per year	Singh (2006), Yusoff and Hansen (2007), Unilever (1990)
GHG emissions of and after plantation	100.22	g CO_2 eq per kg FFB	Note: Entire palm kernels not used for CPO but higher valued products. Energy content of EPK considered, but not the higher economic value of PKO produced via cold pressing
GHG emissions of and after plantation	452.35	g CO_2 eq per kg RefPO	
GHG emissions of and after plantation	12.23	g CO_2 eq per MJ RefPO	
Oil mill			
Main output			
Produced CPO	199.8	t CPO per 1,000 t FFB per year	Malaysian average 2003–2005 given in MPOB (2005) and MPOB (2006)
Palm kernel oil (by-product)	0	t PKO per 1,000 t FFB per year	
Palm kernel meal (by-product)	0	t PKM per 1,000 t FFB per year	
Entire palm kernels (by-product)	53.2	t EPK per 1,000 t FFB per year	Malaysian average 2003–2005 given in MPOB (2005) and MPOB (2006)
Input/POME			
n-Hexane	0	t per 1,000 t FFB per year	Schmidt (2007)
CH_4 emissions from POME	1,093.6	g CO_2 eq per kg CPO	Calculations based on Yacob et al. (2006), Ma et al. (2004), Singh (1999), Andersen et al. (1981)
Energy consumption			
Fuel oil	370	l per 1,000 t FFB per year	Subranamiam et al. (2005)

Table 6 continued

	Value	Unit	Source
Natural gas	0	kWh per 1,000 t FFB per year	Subranamiam et al. (2005), Henson (2004), Department of Environment (1999)
Electricity (external)	0	kWh per 1,000 t FFB per year	Subranamiam et al. (2005), Henson (2004), Department of Environment (1999)
Surplus electricity (output)	8,900.0	kWh per 1,000 t FFB per year	Schmidt (2007), Husain et al. (2003), Singh and Thorairaj (2006), Chavalparit et al. (20060
Surplus steam (output)	0	kWh per 1,000 t FFB per year	Subranamiam (2006a)
Allocation factor after by-products	*0.863*		
Transport			
Average distance plantation/oil mill	–		Note: Diesel use for transport already covered in the cultivation stage
GHG emissions after oil mill	1,345.32	g CO_2 eq per kg CPO	
GHG emissions of oil mill	953.51	g CO_2 eq per kg RefPO	
GHG emissions of oil mill	25.77	g CO_2 eq per MJ RefPO	
Refinery			
Output			
Produced RefPO	957	t RefPO per 1,000 t CPO per year	Schmidt (2007), Singh (2006), Kang (2006), UPRD (2004)
Input			
Fuller's earth	4.3	t per 1,000 t CPO per year	UPRD (2004)
Energy consumption			
Natural gas	0	kWh per 1,000 t CPO per year	
Fuel oil	8,612	l per 1,000 t CPO per year	Schmidt (2007)
Electricity (external)	33,493	kWh per 1,000 t CPO per year	Schmidt (2007)
Electricity mix	Malaysia (high value)		JEC E3-database, version 31-7-2008
GHG emission after refinery	1,440.44	g CO_2 eq per kg RefPO	
GHG emissions of refinery	34.58	g CO_2 eq per kg RefPO	
GHG emissions of refinery	0.93	g CO_2 eq per MJ RefPO	
Transport (to Europe)			
Transport (overland)			
Average distance oil mill/refinery/port	200	km	Schmidt (2007)

Table 6 continued

	Value	Unit	Source
Vehicle used transporting RefPO	Truck for liquids (Diesel)		Schmidt (2007)
Used fuel for vehicle	Diesel		Schmidt (2007)
Transport (ship)			
Average distance Asia-Europe	14,975	km	PortWorld Distances (2011)
Vehicle used transporting RefPO	Ship/tanker 50kt (Fuel oil)		Schmidt (2007)
Used fuel for vehicle	HFO		Schmidt (2007)
GHG emissions after transport	1,623.59	g CO_2 eq per kg RefPO	
GHG emissions of transport	183.15	g CO_2 eq per kg RefPO	
GHG emissions of transport	4.95	g CO_2 eq per MJ RefPO	
Total GHG emissions RefPO	1,623.59	g CO_2 eq per kg RefPO	
	43.88	g CO_2 eq per MJ RefPO	
GHG emission savings RefPO compared with fossil comparator (electricity production)	52.0 %	91 g CO_2 eq/MJ (RED 2009/28/EC)	
Esterification			
CO_2 emissions after Esterification	1,896.49	g CO_2 eq per kg FAME	
CO_2 emissions of esterification	264.12	g CO_2 eq per kg FAME	Weindorf (2008)
CO_2 emissions of esterification	7.10	g CO_2 eq per MJ FAME	Weindorf (2008)
Total CO_2 emissions FAME	1,896.49	g CO_2 eq per kg FAME	
Total CO_2 emissions FAME	51.53	g CO_2 eq per MJ FAME	

		Fossil comparator
GHG emission savings compared with fossil comparator I (fuel diesel)	38.5 %	83.8 g CO_2 eq/MJ (RED 2009/28/EC)
GHG emission savings compared with fossil comparator II (fuel diesel)	41.0 %	87.3 g CO_2 eq/MJ (Silva et al. 2006; CONCAWE et al. 2006)

Even if we rely on the inferior values for esterification (WTT Appendix v3) but using the same figures for plantation, milling, refinery, and transport as in scenario 3, the results exceed the 35 % threshold (all comparators (see scenario 4 in Table 11, with emission savings of 55.0 % (electricity) 37.8 % (fuel I) and 40.3 % (fuel II)).

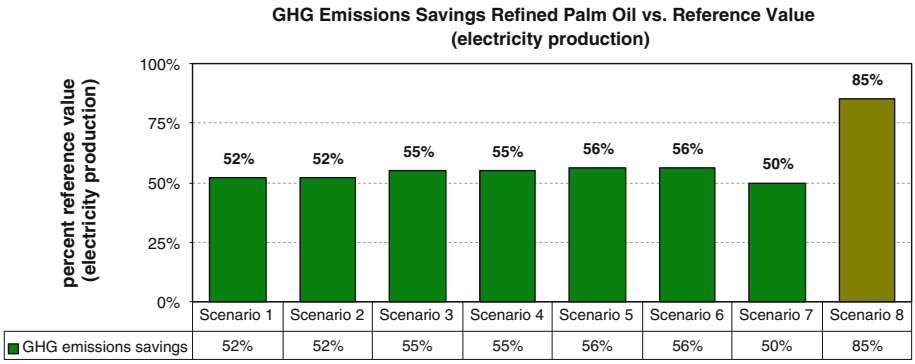


Fig. 2 GHG emissions savings of refined palm oil used in oil fired power plants

Table 7 Overview scenario assumptions

Scenario	Main assumptions
Scenario 1	Average values plantation, oil mill, refinery, transport; current values esterification
Scenario 2	Average values plantation, oil mill, refinery, transport; conservative values esterification
Scenario 3	Current values plantation, oil mill, refinery, transport, esterification
Scenario 4	Current values plantation, oil mill, refinery, transport; conservative values esterification
Scenario 5	Current values plantation, oil mill, refinery; transport according JEC; current values esterification
Scenario 6	Current values plantation, oil mill, refinery; transport according JEC; conservative values esterification
Scenario 7	Palm kernel oil as additional by-product; current values plantation, oil mill, refinery, transport, esterification
Scenario 8	Methane capturing in oil mill; current values plantation, oil mill, refinery; transport according JEC; current values esterification

In scenario 5 (Table 12) and 6 (Table 13), respectively, we run the same estimation as in scenarios 3 (esterification according Weindorf 2008) and 4 (esterification according CONCAWE et al. 2006), but using the JEC (2011) default value on transport stage of 135 g CO_2 eq per kg RefPO (see JEC E3-database (version 31-7-2008)). As this default value is lower than our conservative transport figures, higher GHG emissions saving values [56.0 % (electricity), 43.2 % (fuel I), 45.5 % (fuel II) for scenario 5 and 56.0 % (electricity), 39.3 % (fuel I), 41.8 % (fuel II) for scenario 6]—all above the EU emission target of 35 %—could be estimated.

Even if we analyse the production chain of palm biodiesel under consideration of a further processing (and the supplemental energy input) of the entire palm kernels to palm kernel oil and palm kernel meal (scenario 7, Table 14), we could derive emission saving figures (50.0 % (electricity), 37.1 % (fuel I), 39.6 % (fuel II)) well exceeding the EU target.

Again, we use the latest values on input and output figures as in scenario 3. It is important to note that only the caloric heating value of these by-products is considered in our estimation. However, these products are high valued stocks with an economic value

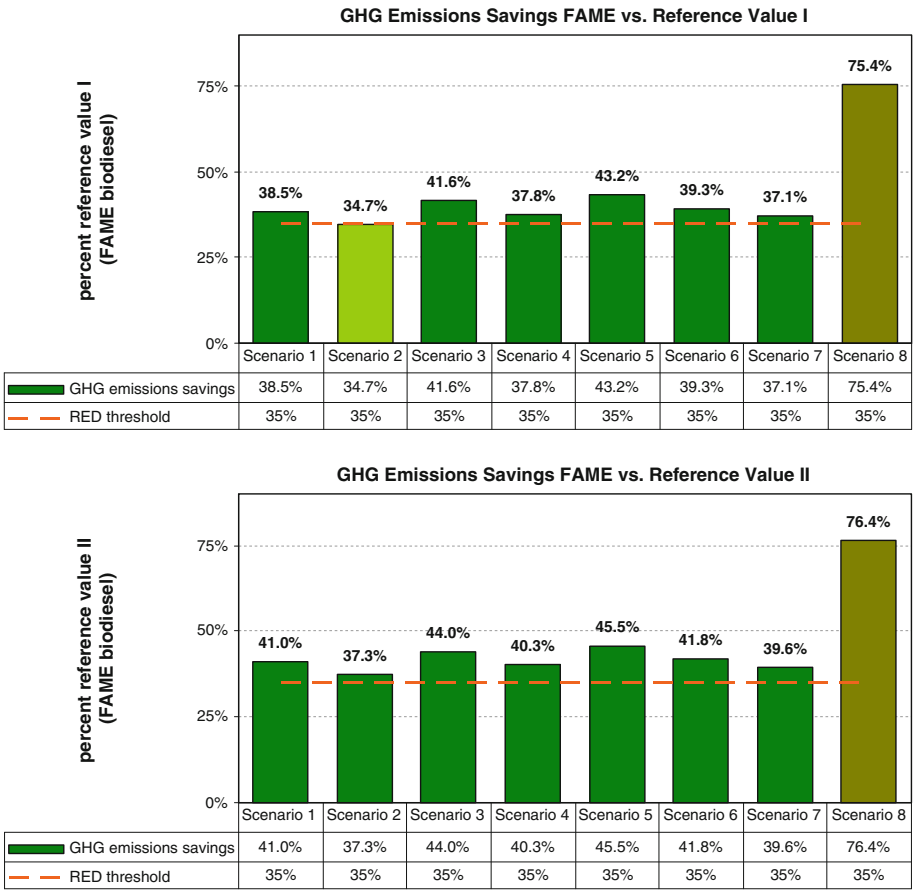


Fig. 3 GHG emissions savings of palm oil–based biofuel

considerably exceeding the caloric value. Palm kernel oil is used as edible oil in food production, while palm kernel meal is sold as fodder for livestock, replacing the use of soybean meal. That is why the pure energy content allocation does not reflect the real allocation pattern. Basically, we suggest to alternatively considering the economic allocation in LCA which better reflects the economic and social impact of the whole production chain. However, in this study, we refrain from doing so because we want to be as close as possible to the current methodology used by the European Union (EU) (2009).

In the last scenario (scenario 8, Table 15), we apply a technology not yet commonly used but not unusual either, namely methane capturing (and using as bio gas) of POME emissions in the palm oil mill. As in scenario 5, we use the latest values with the transport default value according to JEC (2011). The emission savings values figure with 85.0 % compared with conventional electricity production, and 75.4 % (EU 2009) respective 76.4 % (CONCAWE et al. 2006; Silva et al. 2006) compared with fossil diesel. These saving values are not only way beyond the RED's thresholds but also far higher than the GHG emissions savings calculated by the Directive typical (62 %) and default (56 %) values given in the case of palm oil with methane capture.

Overall, our conservative calculations based on JEC (2011) background data and current publications on palm oil production result in GHG emissions saving potentials of palm oil–based biodiesel fairly above the 35 % threshold. We could not reproduce the EU's GHG saving values for palm oil. Our results rather confirm the higher values obtained by other studies mentioned in our last paper (Pehnelt and Vietze 2009) and elsewhere in this study.

5 Summary and conclusion

The purpose of this review was to gain a comprehensive understanding of the metrics considered in developing the GHG emissions saving values (typical and default) in the Directive, utilising palm oil—one of the more controversial biofuel sources—as a case study of this process. Unfortunately, the conclusions of this analysis demonstrate that the methodology employed by the JRC lacks credibility, and subsequent efforts to gain further clarity from the JRC were not successful. As a result, the authors of this report support the efforts by environmental NGOs to gain further clarity on the European Commission's and EU's calculations and deliberations on the assessment of biofuels, and institute greater transparency in the process.

Based on the standard calculation scheme proposed by the Renewable Energy Directive (European Union (EU) 2009) and using current data of palm oil biodiesel production published in various reliable sources, we cannot reproduce the GHG emissions saving values for palm oil biodiesel given in the annex of the RED. In contrast, our results indicate emissions saving values for the GHG emissions savings potential of palm oil biodiesel not only far above the 19 per cent default and 36 per cent typical value published in RED but also beyond the 35 per cent threshold. Our results confirm the findings by other studies and challenge the official typical and default values published in RED.

These findings and concerns surrounding the trade implications of the Directive give cause for serious concern within the EU community regarding the viability of the system to effectively deliver the GHG emissions savings that are required in the legislation. While limiting imports of inefficient and environmentally damaging biofuel sources should be supported, distorting technical parameters in legislation to limit entry into the European market would be costly for consumers and businesses while exposing the EU to unnecessary trade disputes and possible retaliation.

The EU has been a leader in the promotion of low-carbon solutions to energy needs and the development of technologies that will spur a new age of energy generation and transportation. Unfortunately, since the EU began to pursue this goal, the debate has increasingly turned to how these efforts can be increasingly limited, through introduction of new, untested sustainability criteria and trade barriers to limit competition from third countries. Not only will these measures undermine confidence in Europe's low-carbon ambitions, however, they will also harm the global cooperation that is a key to achieving these goals.

Appendix

See Tables 8, 9, 10, 11, 12, 13, 14, 15.

Table 8 Background data

Global warming potentials (GWP's)					gCO_2-eq/g
CO_2					1.00
CH_4					25.00
N_2O					298.00
Agro inputs	GHG emission coefficient				Fossil energy input
	gCO_2/kg	gCH_4/kg	gN_2O/kg	gCO_2-eq/kg	MJfossil/kg
N-fertiliser (kg N)	2,827.005	8.679	9.642	5,917.231	48.99
P_2O_5-fertiliser (kg P_2O_5)	964.887	1.331	0.052	1,013.509	15.23
K_2O-fertiliser (kg K_2O)	536.311	1.571	0.012	579.249	9.68
CaO-fertiliser (kg CaO)	119.116	0.216	0.018	129.967	1.97
Pesticides	9,886.502	25.527	1.681	11,025.737	268.40
	GHG emission coefficient				Fossil energy input/heat input rate (LHV)	
	gCO_2/MJ	gCH_4/MJ	gN_2O/MJ	gCO_2-eq/MJ	MJfossil/MJ	MJ/kg
Fuels (gas)						
Natural gas (4,000 km, Russian NG quality)	61.575	0.198	0.000	66.595	1.128	
Natural gas (4,000 km, EU Mix quality)	62.964	0.198	0.000	67.984	1.128	
Methane						50.00
Fuels: liquids (also conversion inputs)						
Diesel	87.64	0.00	0.00	87.64	1.16	43.10
Gasoline	–	–	–	–		43.20
HFO	84.98	0.00	0.00	84.98	1.09	40.50
HFO for maritime transport	87.20	0.00	0.00	87.20	1.09	40.50
Ethanol	–	–	–	–		26.81
Methanol	92.80	0.29	0.00	100.15	1.66	19.90

Table 8 continued

	GHG emission coefficient				Fossil energy input/heat input rate (LHV)	
	gCO_2/MJ	gCH_4/MJ	gN_2O/MJ	gCO_2-eq/MJ	MJfossil/MJ	MJ/kg
FAME	–	–	–	–		37.20
Syn diesel (BtL)	–	–	–	–		44.00
HVO	–	–	–	–		44.00
PVO	–	–	–	–		36.00

Fuels/feedstock/byproducts—solids	LHV MJ/kg
FFB	24.00
BioOil (byproduct FAME from waste oil)	21.80
Glycerol	16.00
Palm kernel meal	17.00
Palm oil	37.00

Electricity	GHG emission coefficient				Fossil energy input
	gCO_2/MJ	gCH_4/MJ	gN_2O/MJ	gCO_2-eq/MJ	MJfossil/MJ
Electricity EU mix MV	119.36	0.29	0.01	128.25	2.70
Electricity EU mix LV	120.79	0.29	0.01	129.79	2.73

Conversion inputs	GHG emission coefficient				Fossil energy input	LHV
	gCO_2/MJ	gCH_4/MJ	gN_2O/MJ	gCO_2-eq/MJ	MJfossil/MJ	MJ/kg
n-Hexane	80.08	0.01	0.00	80.53	0.32	45.11

	gCO_2/kg	gCH_4/kg	gN_2O/kg	gCO_2-eq/kg	MJ/kg
Phosphoric acid (H_3PO_4)	2,776.00	8.93	0.10	3,029.80	28.57
Fuller's earth	197.00	0.04	0.01	199.81	2.54

Table 8 continued

	gCO_2/kg	gCH_4/kg	gN_2O/kg	gCO_2-eq/kg	MJ/kg
Hydrochloric acid (HCl)	717.38	1.13	0.03	753.17	15.43
Sodium carbonate (Na_2CO_3)	1,046.00	6.20	0.01	1,202.64	13.79
Sodium hydroxide (NaOH)	438.49	1.03	0.02	471.40	10.22
Pure CaO for processes	1,013.00	0.65	0.01	1,031.49	4.60
Sulphuric acid (H_2SO_4)	193.85	0.55	0.00	208.83	3.90

Transport efficiencies	Fuel efficiency	Transport exhaust gas emissions	
	MJ/tkm	gCH_4/tkm	gN_2O/tkm
Truck for dry product (Diesel)	0.94	0.01	0.00
Truck for liquids (Diesel)	1.01	0.01	0.00
Truck for FFB transport (Diesel)	2.01	0.01	0.00
Tanker truck MB2218 for vinasse transport	2.16	0.00	0.00
Tanker truck with water cannons	0.94	0.00	0.00
Dumpster truck MB2213 for filter mud transport	3.60	0.00	0.00
Ocean bulk carrier (Fuel oil)	0.20	0.00	0.00
Ship/product tanker 50kt (Fuel oil)	0.12	0.00	0.00
Local (10 km) pipeline	0.00	0.00	0.00
Rail (Electric, MV)	0.21	0.00	0.00

Emissions from steam production	GHG emission coefficient		
	gCH_4/MJ	gN_2O/MJ	gCO_2-eq/MJ
CH_4 and N_2O emissions from NG boiler	0.00	0.00	0.40
CH_4 and N_2O emissions from NG CHP	0.00	0.00	0.00

Table 8 continued

Electricity production	GHG emission coefficient				Fossil energy input
	gCO_2/MJ	gCH_4/MJ	gN_2O/MJ	gCO_2-eq/MJ	MJfossil/MJ
Electricity (NG CCGT)	114.48	0.37	0.00	10.68	2.05
Electricity (Lignite ST)	284.77	0.03	0.01	2.96	2.48
Electricity (Straw ST)	5.56	0.00	0.00	0.16	0.08

Other GHG-related values	LHV MJ/kg
Palm kernels	22.00
Palm kernel oil	35.50

	GHG emission coefficient	
	gCH_4/kg CPO	gCO_2-eq/kg CPO
POME emissions (JEC E3-database, version 31-7-2008)	48.90	1,222.62
POME emissions (Singh 1999/Ma et al. 2004/Andersen et al. 1981/Yacob et al. 2006)	43.74	1,093.59
POME emissions (Ma et al. 2004/Yacob et al. 2006)	43.55	1,088.71

	gCO_2-eq/MJ
Natural gas in steam boiler	70.66
Electricity Ghana	146.56
Electricity Indonesia	279.47
Electricity Kenya	91.53
Electricity Malaysia	252.71
Electricity Thailand	235.89

Source: JEC E3-database (version 31-7-2008)

Table 9 Scenario 2—entire PK, esterification WTT (CONCAWE et al. 2006) standard

	Value	Unit	Source
Plantation			
Output			
Yield FFB per ha	18,870	kg FFB per ha per year	FAOSTAT (2006)
Input			
N-fertiliser	105	kg N per ha per year	Yusoff and Hansen (2007), Subranamiam (2006a), UPB (2006), FAO (2004), Henson (2004), IFA et al. (2002)
P_2O_5-fertiliser	70	kg P_2O_5 per ha per year	Yusoff and Hansen (2007), Subranamiam (2006a), UPB (2006), FAO (2004), Henson (2004), IFA et al. (2002)
K_2O-fertiliser	204	kg K_2O per ha per year	Yusoff and Hansen (2007), Subranamiam (2006a), UPB (2006), FAO (2004), Henson (2004), IFA et al. (2002)
CaO-fertiliser	0	kg CaO per ha per year	Yusoff and Hansen (2007), Subranamiam (2006a), UPB (2006), FAO (2004), Henson (2004), IFA et al. (2002)
Pesticides	2.73	kg active ingredient per ha per year	Singh (2006)
Diesel (for all activities and transport)	58.2	l per ha per year	Singh (2006), Yusoff and Hansen (2007), Unilever (1990)
GHG emissions of and after plantation	100.22	g CO_2 eq per kg FFB	*Note*: Entire Palm kernels not used for CPO but higher valued products. Energy content of EPK considered, but not the higher economic value of PKO produced via cold pressing
GHG emissions of and after plantation	452.35	g CO_2 eq per kg RefPO	
GHG emissions of and after plantation	12.23	g CO_2 eq per MJ RefPO	
Oil mill			
Main output			
Produced CPO	199.8	t CPO per 1,000 t FFB per year	Malaysian average 2003–2005 given in MPOB (2005) and MPOB (2006)
Palm kernel oil (by-product)	0	t PKO per 1,000 t FFB per year	
Palm kernel meal (by-product)	0	t PKM per 1,000 t FFB per year	
Entire palm kernels (by-product)	53.2	t EPK per 1,000 t FFB per year	Malaysian average 2003–2005 given in MPOB (2005) and MPOB (2006)
Input/POME			
n-Hexane	0	t per 1,000 t FFB per year	Schmidt (2007)
CH_4 emissions from POME	1,093.6	g CO_2 eq per kg CPO	Calculations based on Yacob et al. (2006), Ma et al. (2004), Singh (1999), Andersen et al. (1981)

Table 9 continued

	Value	Unit	Source
Energy consumption			
Fuel oil	370	l per 1,000 t FFB per year	Subranamiam et al. (2005)
Natural gas	0	kWh per 1,000 t FFB per year	Subranamiam et al. (2005), Henson (2004), Department of Environment (1999)
Electricity (external)	0	kWh per 1,000 t FFB per year	Subranamiam et al. (2005), Henson (2004), Department of Environment (1999)
Surplus electricity (output)	8,900	kWh per 1,000 t FFB per year	Schmidt (2007), Husain et al. (2003), Singh and Thorairaj (2006), Chavalparit et al. (2006)
Surplus steam (output)	0	kWh per 1,000 t FFB per year	Subranamiam (2006a)
Allocation factor after by-products	*0.863*		
Transport			
Average distance plantation/oil mill	–		*Note*: Diesel use for transport already covered in the cultivation stage.
GHG emissions after oil mill	1,345.32	g CO_2 eq per kg CPO	
GHG emissions of oil mill	953.51	g CO_2 eq per kg RefPO	
GHG emissions of oil mill	25.77	g CO_2 eq per MJ RefPO	
Refinery			
Output			
Produced RefPO	957	t RefPO per 1,000 t CPO per year	Schmidt (2007), Singh (2006), Kang (2006), UPRD (2004)
Input			
Fuller's earth	4.3	t per 1,000 t CPO per year	UPRD (2004)
Energy consumption			
Natural gas	0	kWh per 1,000 t CPO per year	Schmidt (2007)
Fuel oil	8,612	l per 1,000 t CPO per year	Schmidt (2007)
Electricity (external)	33,493	kWh per 1,000 t CPO per year	Schmidt (2007)
Electricity mix	Malaysia (high value)		JEC E3-database, version 31-7-2008
GHG emission after refinery	1,440.44	g CO_2 eq per kg RefPO	
GHG emissions of refinery	34.58	g CO_2 eq per kg RefPO	
GHG emissions of refinery	0.93	g CO_2 eq per MJ RefPO	

Table 9 continued

	Value	Unit	Source
Transport (to Europe)			
Transport (overland)			
Average distance oil mill/refinery/port	200	km	Schmidt (2007)
Vehicle used transporting RefPO	Truck for liquids (Diesel)		Schmidt (2007)
Used fuel for vehicle	Diesel		Schmidt (2007)
Transport (ship)			
Average distance Asia-Europe	14,975	km	PortWorld Distances (2011)
Vehicle used transporting RefPO	Ship/tanker 50kt (Fuel oil)		Schmidt (2007)
Used fuel for vehicle	HFO		Schmidt (2007)
GHG emissions after transport	1,623.59	g CO_2 eq per kg RefPO	
GHG emissions of transport	183.15	g CO_2 eq per kg RefPO	
GHG emissions of transport	4.95	g CO_2 eq per MJ RefPO	
Total GHG emissions RefPO	1,623.59	g CO_2 eq per kg RefPO	
	43.88	g CO_2 eq per MJ RefPO	
GHG emission savings RefPO compared with fossil comparator (electricity production)	52.0 %	91 g CO_2 eq/MJ (RED 2009/28/EC)	
Esterification			
CO_2 emissions after esterification	2,015.15	g CO_2 eq per kg FAME	
CO_2 emissions of esterification	382.79	g CO_2 eq per kg FAME	Calculations based on WTT Appendix (v3)
CO_2 emissions of esterification	10.29	g CO_2 eq per MJ FAME	Calculations based on WTT Appendix (v3)
Total CO_2 emissions FAME	2,015.15	g CO_2 eq per kg FAME	
Total CO_2 emissions FAME	54.76	g CO_2 eq per MJ FAME	

		Fossil comparator
GHG emission savings compared with fossil comparator I (fuel diesel)	34.7 %	83.8 g CO_2 eq/MJ (RED 2009/28/EC)
GHG emission savings compared with fossil comparator II (fuel diesel)	37.3 %	87.3 g CO_2 eq/MJ (Silva et al. 2006; CONCAWE et al. 2006)

Table 10 Scenario 3—Entire PK, latest values

	Value	Unit	Source
Plantation			
Output			
Yield FFB per ha	20,900	kg FFB per ha per year	FAOSTAT (2006)
Input			
N-fertiliser	95.52	kg N per ha per year	Average of Yusoff and Hansen (2007), Henson (2004)
P_2O_5-fertiliser	28.56	kg P_2O_5 per ha per year	Average of Yusoff and Hansen (2007), Henson (2004)
K_2O-fertiliser	169.44	kg K_2O per ha per year	Average of Yusoff and Hansen (2007), Henson (2004)
CaO-fertiliser	0	kg CaO per ha per year	Average of Yusoff and Hansen (2007), Henson (2004)
Pesticides	2.73	kg active ingredient per ha per year	Singh (2006)
Diesel (for all activities and transport)	53.6	l per ha per year	Singh (2006)
GHG emissions of and after plantation	80.40	g CO_2 eq per kg FFB	*Note*: Entire palm kernels not used for CPO but higher valued products. Energy content of EPK considered, but not the higher economic value of PKO produced via cold pressing
GHG emissions of and after plantation	360.04	g CO_2 eq per kg RefPO	
GHG emissions of and after plantation	9.73	g CO_2 eq per MJ RefPO	
Oil mill			
Main output			
Produced CPO	201.5	t CPO per 1,000 t FFB per year	Malaysian average in 2005 given in MPOB (2006)
Palm kernel oil (by-product)	0	t PKO per 1,000 t FFB per year	
Palm kernel meal (by-product)	0	t PKM per 1,000 t FFB per year	
Entire palm kernels (by-product)	53.4	t EPK per 1,000 t FFB per year	Malaysian average in 2005 given in MPOB (2006)
Input/POME			
n-Hexane	0	t per 1,000 t FFB per year	
CH_4 emissions from POME	1088.7	g CO_2 eq per kg CPO	Calculations based on Yacob et al. (2006), Ma et al. (2004), Andersen et al. (1981)
Energy consumption			
Fuel oil	370	l per 1,000 t FFB per year	Subranamiam et al. (2005)
Natural gas	0	kWh per 1,000 t FFB per year	Subranamiam et al. (2005), Henson (2004), Department of Environment (1999)
Electricity (external)	0	kWh per 1,000 t FFB per year	Subranamiam et al. (2005), Henson (2004), Department of Environment (1999)
Surplus electricity (output)	8,900	kWh per 1,000 t FFB per year	Schmidt (2007), Husain et al. (2003), Singh and Thorairaj (2006), Chavalparit et al. (2006)

Table 10 continued

	Value	Unit	Source
Surplus steam (output)	0	kWh per 1,000 t FFB per year	Subranamiam (2006a)
Allocation factor after by-products	*0.864*		
Transport			
Average distance plantation/oil mill	–		Note: Diesel use for transport already covered in the cultivation stage
GHG emissions after Oil Mill	1,253.85	g CO_2 eq per kg CPO	
GHG emissions of Oil Mill	950.22	g CO_2 eq per kg RefPO	
GHG emissions of Oil Mill	25.68	g CO_2 eq per MJ RefPO	
Refinery			
Output			
Produced RefPO	957	t RefPO per 1,000 t CPO per year	Schmidt (2007), Singh (2006), Kang (2006), UPRD (2004)
Input			
Fuller's earth	4.3	t per 1,000 t CPO per year	UPRD (2004)
Energy consumption			
Natural gas	0	kWh per 1,000 t CPO per year	Schmidt (2007)
Fuel oil	8,612	l per 1,000 t CPO per year	Schmidt (2007)
Electricity (external)	33,493	kWh per 1,000 t CPO per year	Schmidt (2007)
Electricity mix	Malaysia (high value)		JEC E3-database, version 31-7-2008
GHG emission after refinery	1,344.85	g CO_2 eq per kg RefPO	
GHG emissions of refinery	34.58	g CO_2 eq per kg RefPO	
GHG emissions of refinery	0.93	g CO_2 eq per MJ RefPO	
Transport (to Europe)			
Transport (overland)			
Average distance oil mill/refinery/port	200	km	Schmidt (2007)
Vehicle used transporting RefPO	Truck for liquids (Diesel)		Schmidt (2007)
Used fuel for vehicle	Diesel		Schmidt (2007)
Transport (ship)			
Average distance Asia-Europe	14,975	km	PortWorld Distances (2011)

Table 10 continued

	Value	Unit	Source
Vehicle used transporting RefPO	Ship/tanker 50kt (Fuel oil)		Schmidt (2007)
Used fuel for vehicle	HFO		Schmidt (2007)
GHG emissions after Transport	1,527.99	g CO_2 eq per kg RefPO	
GHG emissions of Transport	183.15	g CO_2 eq per kg RefPO	
GHG emissions of Transport	4.95	g CO_2 eq per MJ RefPO	
Total GHG emissions RefPO	1,527.99	g CO_2 eq per kg RefPO	
	41.30	g CO_2 eq per MJ RefPO	
GHG emission savings RefPO compared with fossil comparator (electricity production)	55.0 %	91 g CO_2 eq/MJ (RED 2009/28/EC)	
Esterification			
CO_2 emissions after Esterification	1,800.37	g CO_2 eq per kg FAME	
CO_2 emissions of Esterification	264.12	g CO_2 eq per kg FAME	Weindorf (2008)
CO_2 emissions of Esterification	7.10	g CO_2 eq per MJ FAME	Weindorf (2008)
Total CO_2 emissions FAME	1,800.37	g CO_2 eq per kg FAME	
Total CO_2 emissions FAME	48.92	g CO_2 eq per MJ FAME	

		Fossil comparator
GHG emission savings compared with fossil comparator I (fuel diesel)	41.6 %	83.8 g CO_2 eq/MJ (RED 2009/28/EC)
GHG emission savings compared with fossil comparator II (fuel diesel)	44.0 %	87.3 g CO_2 eq/MJ (Silva et al. 2006, CONCAWE et al. 2006)

Table 11 Scenario 4—Entire PK, latest values, esterification WTT (CONCAWE et al. 2006) standard

	Value	Unit	Source
Plantation			
Output			
Yield FFB per ha	20,900	kg FFB per ha per year	FAOSTAT (2006)
Input			
N-fertiliser	95.52	kg N per ha per year	Average of Yusoff and Hansen (2007), Henson (2004)
P_2O_5-fertiliser	28.56	kg P_2O_5 per ha per year	Average of Yusoff and Hansen (2007), Henson (2004)

Table 11 continued

	Value	Unit	Source
K_2O-fertiliser	169.44	kg K_2O per ha per year	Average of Yusoff and Hansen (2007), Henson (2004)
CaO-fertiliser	0	kg CaO per ha per year	Average of Yusoff and Hansen (2007), Henson (2004)
Pesticides	2.73	kg active ingredient per ha per year	Singh (2006)
Diesel (for all activities and transport)	53.6	l per ha per year	Singh (2006)
GHG emissions of and after plantation	80.40	g CO_2eq per kg FFB	*Note*: Entire palm kernels not used for CPO but higher valued products. Energy content of EPK considered, but not the higher economic value of PKO produced via cold pressing
GHG emissions of and after plantation	360.04	g CO_2 eq per kg RefPO	
GHG emissions of and after plantation	9.73	g CO_2 eq per MJ RefPO	
Oil mill			
Main output			
Produced CPO	201.5	t CPO per 1,000 t FFB per year	Malaysian average in 2005 given in MPOB (2006)
Palm kernel oil (by-product)	0	t PKO per 1,000 t FFB per year	
Palm kernel meal (by-product)	0	t PKM per 1,000 t FFB per year	
Entire palm kernels (by-product)	53.4	t EPK per 1,000 t FFB per year	Malaysian average in 2005 given in MPOB (2006)
Input/POME			
n-Hexane	0	t per 1,000 t FFB per year	
CH_4 emissions from POME	1,088.7	g CO_2 eq per kg CPO	Calculations based on Yacob et al. (2006), Ma et al. (2004), Andersen et al. (1981)
Energy consumption			
Fuel oil	370	l per 1,000 t FFB per year	Subranamiam et al. (2005)
Natural gas	0	kWh per 1,000 t FFB per year	Subranamiam et al. (2005), Henson (2004), Department of Environment (1999)
Electricity (external)	0	kWh per 1,000 t FFB per year	Subranamiam et al. (2005), Henson (2004), Department of Environment (1999)
Surplus electricity (output)	8,900	kWh per 1,000 t FFB per year	Schmidt (2007), Husain et al. (2003), Singh and Thorairaj (2006), Chavalparit et al. (2006)
Surplus steam (output)	0	KWh per 1,000 t FFB per year	Subranamiam (2006a)
Allocation factor after by-products	*0.864*		
Transport			
Average distance plantation/oil mill	–		*Note*: Diesel use for transport already covered in the cultivation stage

Table 11 continued

	Value	Unit	Source
GHG emissions after Oil Mill	1,253.85	g CO_2 eq per kg CPO	
GHG emissions of Oil Mill	950.22	g CO_2 eq per kg RefPO	
GHG emissions of Oil Mill	25.68	g CO_2 eq per MJ RefPO	
Refinery			
Output			
Produced RefPO	957	T RefPO per 1,000 t CPO per year	Schmidt (2007), Singh (2006), Kang (2006), UPRD (2004)
Input			
Fuller's earth	4.3	t per 1,000 t CPO per year	UPRD (2004)
Energy consumption			
Natural gas	0	kWh per 1,000 t CPO per year	Schmidt (2007)
Fuel oil	8,612	l per 1,000 t CPO per year	Schmidt (2007)
Electricity (external)	33,493	kWh per 1,000 t CPO per year	Schmidt (2007)
Electricity mix	Malaysia (high value)		JEC E3-database, version 31-7-2008
GHG emission after refinery	1,344.85	g CO_2 eq per kg RefPO	
GHG emissions of refinery	34.58	g CO_2 eq per kg RefPO	
GHG emissions of refinery	0.93	g CO_2 eq per MJ RefPO	
Transport (to Europe)			
Transport (overland)			
Average distance oil mill/refinery/port	200	km	Schmidt (2007)
Vehicle used transporting RefPO	Truck for liquids (Diesel)		Schmidt (2007)
Used fuel for vehicle	Diesel		Schmidt (2007)
Transport (ship)			
Average distance Asia-Europe	14,975	km	PortWorld Distances (2011)
Vehicle used transporting RefPO	Ship/tanker 50 kt (fuel oil)		Schmidt (2007)
Used fuel for vehicle	HFO		Schmidt (2007)
GHG emissions after transport	1,527.99	g CO_2 eq per kg RefPO	
GHG emissions of transport	183.15	g CO_2 eq per kg RefPO	
GHG emissions of transport	4.95	g CO_2 eq per MJ RefPO	

Table 11 continued

	Value	Unit	Source
Total GHG emissions RefPO	1,527.99	g CO_2 eq per kg RefPO	
	41.30	g CO_2 eq per MJ RefPO	
GHG emission savings RefPO compared with fossil comparator (electricity production)	55.0 %	91 g CO_2 eq/MJ (RED 2009/28/EC)	
Esterification			
CO_2 emissions after esterification	1,919.04	g CO_2 eq per kg FAME	
CO_2 emissions of esterification	382.79	g CO_2 eq per kg FAME	Calculations based on WTT Appendix (v3)
CO_2 emissions of esterification	10.29	g CO_2 eq per MJ FAME	Calculations based on WTT Appendix (v3)
Total CO_2 emissions FAME	1,919.04	g CO_2 eq per kg FAME	
Total CO_2 emissions FAME	52.15	g CO_2 eq per MJ FAME	

		Fossil comparator
GHG emission savings compared with fossil comparator I (fuel diesel)	37.8 %	83.8 g CO_2 eq/MJ (RED 2009/28/EC)
GHG emission savings compared with fossil comparator II (fuel diesel)	40.3 %	87.3 g CO_2 eq/MJ (Silva et al. 2006; CONCAWE et al. 2006)

Table 12 Scenario 5—Entire PK, latest values, transport JEC, esterification latest values

	Value	Unit	Source
Plantation			
Output			
Yield FFB per ha	20,900	kg FFB per ha per year	FAOSTAT (2006)
Input			
N-fertiliser	95.52	kg N per ha per year	Average of Yusoff and Hansen (2007), Henson (2004)
P_2O_5-fertiliser	28.56	kg P_2O_5 per ha per year	Average of Yusoff and Hansen (2007), Henson (2004)
K_2O-fertiliser	169.44	kg K_2O per ha per year	Average of Yusoff and Hansen (2007), Henson (2004)
CaO-fertiliser	0	kg CaO per ha per year	Average of Yusoff and Hansen (2007), Henson (2004)
Pesticides	2.73	kg active ingredient per ha per year	Singh (2006)
Diesel (for all activities and transport)	53.6	l per ha per year	Singh (2006)

Table 12 continued

	Value	Unit	Source
GHG emissions of and after plantation	80.40	g CO_2 eq per kg FFB	*Note*: Entire palm kernels not used for CPO but higher valued products. Energy content of EPK considered, but not the higher economic value of PKO produced via cold pressing
GHG emissions of and after plantation	360.04	g CO_2 eq per kg RefPO	
GHG emissions of and after plantation	9.73	g CO_2 eq per MJ RefPO	
Oil mill			
Main output			
Produced CPO	201.5	t CPO per 1,000 t FFB per year	Malaysian average in 2005 given in MPOB (2006)
Palm kernel oil (by-product)	0	t PKO per 1,000 t FFB per year	
Palm kernel meal (by-product)	0	t PKM per 1,000 t FFB per year	
Entire palm kernels (by-product)	53.4	t EPK per 1,000 t FFB per year	Malaysian average in 2005 given in MPOB (2006)
Input/POME			
n-Hexane	0	t per 1,000 t FFB per year	
CH_4 emissions from POME	1,088.7	g CO_2 eq per kg CPO	Calculations based on Yacob et al. (2006), Ma et al. (2004), Andersen et al. (1981)
Energy consumption			
Fuel oil	370	l per 1,000 t FFB per year	Subranamiam et al. (2005)
Natural gas	0	kWh per 1,000 t FFB per year	Subranamiam et al. (2005), Henson (2004), Department of Environment (1999)
Electricity (external)	0	kWh per 1,000 t FFB per year	Subranamiam et al. (2005), Henson (2004), Department of Environment (1999)
Surplus electricity (output)	8,900	kWh per 1,000 t FFB per year	Schmidt (2007), Husain et al. (2003), Singh and Thorairaj (2006), Chavalparit et al. (2006)
Surplus steam (output)	0	kWh per 1,000 t FFB per year	Subranamiam (2006a)
Allocation factor after by-products	*0.864*		
Transport			
Average distance plantation/oil mill	–		*Note*: Diesel use for transport already covered in the cultivation stage
GHG emissions after oil mill	1253.85	g CO_2 eq per kg CPO	
GHG emissions of oil mill	1341.25	g CO_2 eq per kg RefPO	
GHG emissions of oil mill	36.25	g CO_2 eq per MJ RefPO	

Table 12 continued

	Value	Unit	Source
Refinery			
Output			
Produced RefPO	957	T RefPO per 1,000 t CPO per year	Schmidt (2007), Singh (2006), Kang (2006), UPRD (2004)
Input			
Fuller's earth	4.3	t per 1,000 t CPO per year	UPRD (2004)
Energy consumption			
Natural gas	0	kWh per 1,000 t CPO per year	Schmidt (2007)
Fuel oil	8,612	l per 1,000 t CPO per year	Schmidt (2007)
Electricity (external)	33,493	kWh per 1,000 t CPO per year	Schmidt (2007)
Electricity mix	Malaysia (high value)		JEC E3-database, version 31-7-2008
GHG emission after refinery	1,344.85	g CO_2 eq per kg RefPO	
GHG emissions of refinery	34.58	g CO_2 eq per kg RefPO	
GHG emissions of refinery	0.93	g CO_2 eq per MJ RefPO	
Transport (to Europe)			
Transport (overland)			
RED-default value transport	135	g CO_2 eq per kg RefPO	JEC E3-database, version 31-7-2008
GHG emissions after transport	1,479.85	g CO_2 eq per kg RefPO	
GHG emissions of transport	135.00	g CO_2 eq per kg RefPO	
GHG emissions of transport	3.65	g CO_2 eq per MJ RefPO	
Total GHG emissions RefPO	1,479.85	g CO_2 eq per kg RefPO	
	40.00	g CO_2 eq per MJ RefPO	
GHG emission savings RefPO compared with fossil comparator (electricity production)	56.0 %	91 g CO_2 eq/MJ (RED 2009/28/EC)	
Esterification			
CO_2 emissions after Esterification	1,751.97	g CO_2 eq per kg FAME	
CO_2 emissions of Esterification	264.12	g CO_2 eq per kg FAME	Weindorf (2008)
CO_2 emissions of Esterification	7.10	g CO_2 eq per MJ FAME	Weindorf (2008)
Total CO_2 emissions FAME	1,751.97	g CO_2 eq per kg FAME	
Total CO_2 emissions FAME	47.61	g CO_2 eq per MJ FAME	

Table 12 continued

		Fossil comparator
GHG emission savings compared with fossil comparator I (fuel diesel)	43.2 %	83.8 g CO_2 eq/MJ (RED 2009/28/EC)
GHG emission savings compared with fossil comparator II (fuel diesel)	45.5 %	87.3 g CO_2 eq/MJ (Silva et al. 2006; CONCAWE et al. 2006)

Table 13 Scenario 6—Entire PK, latest values, transport RED, esterification WTT (CONCAWE et al. 2006) standard

	Value	Unit	Source
Plantation			
Output			
Yield FFB per ha	20,900	kg FFB per ha per year	FAOSTAT (2006)
Input			
N-fertiliser	95.52	kg N per ha per year	Average of Yusoff and Hansen (2007), Henson (2004)
P_2O_5-fertiliser	28.56	kg P_2O_5 per ha per year	Average of Yusoff and Hansen (2007), Henson (2004)
K_2O-fertiliser	169.44	kg K_2O per ha per year	Average of Yusoff and Hansen (2007), Henson (2004)
CaO-fertiliser	0	kg CaO per ha per year	Average of Yusoff and Hansen (2007), Henson (2004)
Pesticides	2.73	kg active ingredient per ha per year	Singh (2006)
Diesel (for all activities and transport)	53.6	l per ha per year	Singh (2006)
GHG emissions of and after plantation	80.40	g CO_2 eq per kg FFB	*Note*: Entire palm kernels not used for CPO but higher valued products. Energy content of EPK considered, but not the higher economic value of PKO produced via cold pressing
GHG emissions of and after plantation	360.04	g CO_2 eq per kg RefPO	
GHG emissions of and after plantation	9.73	g CO_2 eq per MJ RefPO	
Oil mill			
Main output			
Produced CPO	201.5	t CPO per 1,000 t FFB per year	Malaysian average in 2005 given in MPOB (2006)
Palm kernel oil (by-product)	0	t PKO per 1,000 t FFB per year	
Palm kernel meal (by-product)	0	t PKM per 1,000 t FFB per year	
Entire palm kernels (by-product)	53.4	t EPK per 1,000 t FFB per year	Malaysian average in 2005 given in MPOB (2006)
Input/POME			
n-Hexane	0	t per 1,000 t FFB per year	
CH_4 emissions from POME	1,088.7	g CO_2 eq per kg CPO	Calculations based on Yacob et al. (2006), Ma et al. (2004), Andersen et al. (1981)

Table 13 continued

	Value	Unit	Source
Energy consumption			
Fuel oil	370	l per 1,000 t FFB per year	Subranamiam et al. (2005)
Natural gas	0	kWh per 1,000 t FFB per year	Subranamiam et al. (2005), Henson (2004), Department of Environment (1999)
Electricity (external)	0	kWh per 1,000 t FFB per year	Subranamiam et al. (2005), Henson (2004), Department of Environment (1999)
Surplus electricity (output)	8,900	kWh per 1,000 t FFB per year	Schmidt (2007), Husain et al. (2003), Singh and Thorairaj (2006), Chavalparit et al. (2006)
Surplus steam (output)	0	kWh per 1,000 t FFB per year	Subranamiam (2006a)
Allocation factor after by-products	*0.864*		
Transport			
Average distance plantation/oil mill	–		*Note*: Diesel use for transport already covered in the cultivation stage
GHG emissions after oil mill	1,253.85	g CO_2 eq per kg CPO	
GHG emissions of oil mill	1,341.25	g CO_2 eq per kg RefPO	
GHG emissions of oil mill	36.25	g CO_2 eq per MJ RefPO	
Refinery			
Output			
Produced RefPO	957	t RefPO per 1,000 t CPO per year	Schmidt (2007), Singh (2006), Kang (2006), UPRD (2004)
Input			
Fuller's earth	4.3	t per 1,000 t CPO per year	UPRD (2004)
Energy consumption			
Natural gas	0	kWh per 1,000 t CPO per year	Schmidt (2007)
Fuel oil	8,612	l per 1,000 t CPO per year	Schmidt (2007)
Electricity (external)	33,493	kWh per 1,000 t CPO per year	Schmidt (2007)
Electricity mix	Malaysia (high value)		JEC E3-database, version 31-7-2008
GHG emission after Refinery	1,344.85	g CO_2 eq per kg RefPO	
GHG emissions of Refinery	34.58	g CO_2 eq per kg RefPO	
GHG emissions of Refinery	0.93	g CO_2 eq per MJ RefPO	

Table 13 continued

	Value	Unit	Source
Transport (to Europe)			
Transport (total)			
RED-default value transport	135	g CO_2 eq per kg RefPO	RED (2009/28/EC)
GHG emissions after transport	1,479.85	g CO_2 eq per kg RefPO	
GHG emissions of transport	135.00	g CO_2 eq per kg RefPO	
GHG emissions of transport	3.65	g CO_2 eq per MJ RefPO	
Total GHG emissions RefPO	1,479.85	g CO_2 eq per kg RefPO	
	40.00	g CO_2 eq per MJ RefPO	
GHG emission savings RefPO compared with fossil comparator (electricity production)	56.0 %	91 g CO_2 eq/MJ (RED 2009/28/EC)	
Esterification			
CO_2 emissions after esterification	1,870.63	g CO_2 eq per kg FAME	
CO_2 emissions of esterification	382.79	g CO_2 eq per kg FAME	Weindorf (2008)
CO_2 emissions of esterification	10.29	g CO_2 eq per MJ FAME	Weindorf (2008)
Total CO_2 emissions FAME	1,870.63	g CO_2 eq per kg FAME	
Total CO_2 emissions FAME	50.83	g CO_2 eq per MJ FAME	

		Fossil comparator
GHG emission savings compared with fossil comparator I (fuel diesel)	39.3 %	83.8 g CO_2 eq/MJ (RED 2009/28/EC)
GHG emission savings compared with fossil comparator II (fuel diesel)	41.8 %	87.3 g CO_2 eq/MJ (Silva et al. 2006; CONCAWE et al. 2006)

Table 14 Scenario 7—PKO latest values

	Value	Unit	Source
Plantation			
Output			
Yield FFB per ha	20,900	kg FFB per ha per year	FAOSTAT (2006)
Input			
N-fertiliser	95.52	kg N per ha per year	Average of Yusoff and Hansen (2007), Henson (2004)
P_2O_5-fertiliser	28.56	kg P_2O_5 per ha per year	Average of Yusoff and Hansen (2007), Henson (2004)
K_2O-fertiliser	169.44	kg K_2O per ha per year	Average of Yusoff and Hansen (2007), Henson (2004)

Table 14 continued

	Value	Unit	Source
CaO-fertiliser	0	kg CaO per ha per year	Average of Yusoff and Hansen (2007), Henson (2004)
Pesticides	2.73	kg active ingredient per ha per year	Singh (2006)
Diesel (for all activities and transport)	53.6	l per ha per year	Singh (2006)
GHG emissions of and after plantation	80.40	g CO_2 eq per kg FFB	*Note*: Only calorific value of PKO considered and not the higher economic value of PKO produced via cold pressing (no economic allocation)
GHG emissions of and after plantation	390.72	g CO_2 eq per kg RefPO	
GHG emissions of and after plantation	10.56	g CO_2 eq per MJ RefPO	
Oil mill			
Main output			
Produced CPO	201.5	t CPO per 1,000 t FFB per year	Malaysian average in 2005 given in MPOB (2006)
Palm kernel oil (by-product)	23.97	t PKO per 1,000 t FFB per year	Malaysian average values 2004 according to Oil World (2005)
Palm kernel meal (by-product)	27.83	t PKM per 1,000 t FFB per year	Malaysian average values 2004 according to Oil World (2005)
Entire palm kernels (by-product)	0	t EPK per 1,000 t FFB per year	
Input/POME			
n-Hexane	0	t per 1,000 t FFB per year	
CH_4 emissions from POME	1,088.7	g CO_2 eq per kg CPO	Calculations based on Yacob et al. (2006), Ma et al. (2004), Andersen et al. (1981)
Energy consumption			
Fuel oil	370	l per 1,000 t FFB per year	Subranamiam et al. (2005)
Natural gas	0	kWh per 1,000 t FFB per year	Subranamiam et al. (2005), Henson (2004), Department of Environment (1999)
Electricity (external)	6,404.7	kWh per 1,000 t FFB per year	Only PCO production, Subranamiam (2006b)
Surplus electricity (output)	8,900	kWh per 1,000 t FFB per year	Schmidt (2007); Husain et al. (2003); Singh and Thorairaj (2006); Chavalparit et al. (2006)
Surplus steam (output)	0	kWh per 1000 t FFB per year	Subranamiam (2006a)
Allocation factor after by-products	*0.937*		
Transport			
Average distance plantation/oil mill	–		*Note*: Diesel use for transport already covered in the cultivation stage
GHG emissions after oil mill	1,386.86	g CO_2 eq per kg CPO	
GHG emissions of oil mill	1,058.55	g CO_2 eq per kg RefPO	

Table 14 continued

	Value	Unit	Source
GHG emissions of oil mill	28.61	g CO_2 eq per MJ RefPO	
Refinery			
Output			
Produced RefPO	957	t RefPO per 1,000 t CPO per year	Schmidt (2007), Singh (2006), Kang (2006), UPRD (2004)
Input			
Fuller's earth	4.3	t per 1,000 t CPO per year	UPRD (2004)
Energy consumption			
Natural gas	0	kWh per 1,000 t CPO per year	Schmidt (2007)
Fuel oil	8,612	l per 1,000 t CPO per year	Schmidt (2007)
Electricity (external)	33,493	kWh per 1,000 t CPO per year	Schmidt (2007)
Electricity mix	Malaysia (high value)		JEC E3-database, version 31-7-2008
GHG emission after refinery	1,483.85	g CO_2 eq per kg RefPO	
GHG emissions of refinery	34.58	g CO_2 eq per kg RefPO	
GHG emissions of refinery	0.93	g CO_2 eq per MJ RefPO	
Transport (to Europe)			
Transport (overland)			
Average distance oil mill/refinery/port	200	km	Schmidt (2007)
Vehicle used transporting RefPO	Truck for liquids (Diesel)		Schmidt (2007)
Used fuel for vehicle	Diesel		Schmidt (2007)
Transport (ship)			
Average distance Asia-Europe	14,975	km	PortWorld distances (2011)
Vehicle used transporting RefPO	Ship/tanker 50kt (fuel oil)		Schmidt (2007)
Used fuel for vehicle	HFO		Schmidt (2007)
GHG emissions after transport	1,667.00	g CO_2 eq per kg RefPO	
GHG emissions of transport	183.15	g CO_2 eq per kg RefPO	
GHG emissions of transport	4.95	g CO_2 eq per MJ RefPO	
Total GHG emissions RefPO	1,667.00	g CO_2 eq per kg RefPO	
	45.05	g CO_2 eq per MJ RefPO	

Table 14 continued

	Value	Unit	Source
GHG emission savings RefPO compared with fossil comparator (electricity production)	50.0 %	91 g CO_2 eq/MJ (RED 2009/28/EC)	
Esterification			
CO_2 emissions after esterification	1,940.13	g CO_2 eq per kg FAME	
CO_2 emissions of esterification	264.12	g CO_2 eq per kg FAME	Weindorf (2008)
CO_2 emissions of esterification	7.10	g CO_2 eq per MJ FAME	Weindorf (2008)
Total CO_2 emissions FAME	1,940.13	g CO_2 eq per kg FAME	
Total CO_2 emissions FAME	52.72	g CO_2 eq per MJ FAME	

		Fossil comparator
GHG emission savings compared with fossil comparator I (fuel diesel)	37.1 %	83.8 g CO_2 eq/MJ (RED 2009/28/EC)
GHG emission savings compared with fossil comparator II (fuel diesel)	39.6 %	87.3 g CO_2 eq/MJ (Silva et al. 2006; CONCAWE et al. 2006)

Table 15 Scenario 8—Entire PK latest values, transport RED, methane capture

	Value	Unit	Source
Plantation			
Output			
Yield FFB per ha	20,900	kg FFB per ha per year	FAOSTAT (2006)
Input			
N-fertiliser	95.52	kg N per ha per year	Average of Yusoff and Hansen (2007), Henson (2004)
P_2O_5-fertiliser	28.56	kg P_2O_5 per ha per year	Average of Yusoff and Hansen (2007), Henson (2004)
K_2O-fertiliser	169.44	kg K_2O per ha per year	Average of Yusoff and Hansen (2007), Henson (2004)
CaO-fertiliser	0	kg CaO per ha per year	Average of Yusoff and Hansen (2007), Henson (2004)
Pesticides	2.73	kg active ingredient per ha per year	Singh (2006)
Diesel (for all activities and transport)	53.6	l per ha per year	Singh (2006)
GHG emissions of and after plantation	80.40	g CO_2 eq per kg FFB	*Note*: Entire palm kernels not used for CPO but higher valued products. Energy content of EPK considered, but not the higher economic value of PKO produced via cold pressing

Table 15 continued

	Value	Unit	Source
GHG emissions of and after plantation	360.04	g CO_2 eq per kg RefPO	
GHG emissions of and after plantation	9.73	g CO_2 eq per MJ RefPO	
Oil mill			
Main output			
Produced CPO	201.5	t CPO per 1,000 t FFB per year	Malaysian average in 2005 given in MPOB (2006)
Palm kernel oil (by-product)	0	t PKO per 1,000 t FFB per year	
Palm kernel meal (by-product)	0	t PKM per 1,000 t FFB per year	
Entire palm kernels (by-product)	534	t EPK per 1,000 t FFB per year	Malaysian average in 2005 given in MPOB (2006)
Input/POME			
n-Hexane	0	t per 1,000 t FFB per year	
CH_4 emissions from POME	0.0	g CO_2 eq per kg CPO	Full methane capture
Energy consumption			
Fuel oil	370	l per 1,000 t FFB per year	Subranamiam et al. (2005)
Natural gas	0	kWh per 1,000 t FFB per year	Subranamiam et al. (2005), Henson (2004), Department of Environment (1999)
Electricity (external)	0	kWh per 1,000 t FFB per year	Subranamiam et al. (2005), Henson (2004), Department of Environment (1999)
Surplus electricity (output)	8,900	kWh per 1,000 t FFB per year	Schmidt (2007), Husain et al. (2003), Singh and Thorairaj (2006), Chavalparit et al. (2006)
Surplus steam (output)	0	kWh per 1,000 t FFB per year	Subranamiam (2006a)
Allocation factor after by-products	*0.864*		
Transport			
Average distance plantation/oil mill	–		*Note*: Diesel use for transport already covered in the cultivation stage
GHG emissions after Oil Mill	313.07	g CO_2 eq per kg CPO	
GHG emissions of Oil Mill	−32.89	g CO_2 eq per kg RefPO	
GHG emissions of Oil Mill	−0.89	g CO_2 eq per MJ RefPO	
Refinery			
Output			
Produced RefPO	957	t RefPO per 1,000 t CPO per year	Schmidt (2007), Singh (2006), Kang (2006), UPRD (2004)
Input			
Fuller's earth	4.3	t per 1,000 t CPO per year	UPRD (2004)

Table 15 continued

	Value	Unit	Source
Energy consumption			
Natural gas	0	kWh per 1,000 t CPO per year	Schmidt (2007)
Fuel oil	8,612	l per 1,000 t CPO per year	Schmidt (2007)
Electricity (external)	33,493	kWh per 1,000 t CPO per year	Schmidt (2007)
Electricity mix	Malaysia (high value)		JEC E3-database, version 31-7-2008
GHG emission after Refinery	361.74	g CO_2 eq per kg RefPO	
GHG emissions of Refinery	34.58	g CO_2 eq per kg RefPO	
GHG emissions of Refinery	0.93	g CO_2 eq per MJ RefPO	
Transport (to Europe)			
Transport (total)			
RED-default value transport	135	g CO_2 eq per kg RefPO	JEC E3-database, version 31-7-2008
GHG emissions after transport	496.74	g CO_2 eq per kg RefPO	
GHG emissions of transport	135.00	g CO_2 eq per kg RefPO	
GHG emissions of transport	3.65	g CO_2 eq per MJ RefPO	
Total GHG emissions RefPO	496.74	g CO_2 eq per kg RefPO	
	13.43	g CO_2 eq per MJ RefPO	
GHG emission savings RefPO compared with fossil comparator (electricity production)	85.0 %	91g CO_2 eq/MJ (RED 2009/28/EC)	
Esterification			
CO_2 emissions after esterification	763.54	g CO_2 eq per kg FAME	
CO_2 emissions of esterification	264.12	g CO_2 eq per kg FAME	Weindorf (2008)
CO_2 emissions of esterification	7.10	g CO_2 eq per MJ FAME	Weindorf (2008)
Total CO_2 emissions FAME	763.54	g CO_2 eq per kg FAME	
Total CO_2 emissions FAME	20.64	g CO_2 eq per MJ FAME	

		Fossil comparator
GHG emission savings compared with fossil comparator I (fuel diesel)	75.4 %	83.8 g CO_2 eq/MJ (RED 2009/28/EC)
GHG emission savings compared with fossil comparator II (fuel diesel)	76.4 %	87.3 g CO_2 eq/MJ (Silva et al. 2006; CONCAWE et al. 2006)

References

Andersen, E. S., Jespersgaard, P., & Østergaard, O. G. (1981). *Databog, fysik, kemi (English: Data book, physics, chemistry)*. Copenhagen: F&K forlaget.

Arulandoo, X. (2006). Personal communication with researcher xavier arulandoo, United Plantations Berhad, Research Department, Jendarata Estate, Teluk Intan, Malaysia. In J. H. Schmidt (2007). *Life assessment of rapeseed oil and palm oil. Ph.D. thesis, part 3: Life cycle inventory of rapeseed oil and palm oil*. Diss. Department of Development and Planning, Aalborg University.

Azman, I., & Noor, M. M. (2002). The optimal age of oil palm replanting. *Oil Palm Industry Economic Journal, 2*(1), 11–18.

Bek-Nielsen, C. (2006). Personal communication with Carl Bek-Nielsen, Executive Director, United Plantations Berhan, Teluk Intan, Malaysia. In J. H. Schmidt (2007). *Life assessment of rapeseed oil and palm oil. Ph.D. thesis, part 3: Life cycle inventory of rapeseed oil and palm oil*. Diss. Department of Development and Planning, Aalborg University.

Billore, S. K., Ohsawa, M., Numata, M., & Okano, S. (1995). Microbial biomass nitrogen pool in soils from a warm temperate grassland, and from deciduous and evergreen forests in Chiba, central Japan. *Biology and Fertility of Soils, 19*, 124–128.

BioGrace. (2010). Harmonised calculations of biofuel greenhouse gas emissions in Europe, BioGrace_GHG_calculations_-_version_3_-_Public.xls. BioGrace, Utrecht, The Netherlands et al.

Bockisch, M. (1998). *Fats and oils—Handbook*. Illinois: AOCS Press.

Bundesanstalt für Landwirtschaft und Ernährung (BLE). (2009). *Verordnung über anforderungen an eine nachhaltige Herstellung von Biokraftstoffen (Biokraftstoff-Nachhaltigkeitsverordnung—BiokraftNachV)*. Bonn: BLE.

Casson, A. (2003). *Oil palm, soybeans & critical habitatloss*. Zurich: WWF Switzerland.

Chavalparit, O., Rulkens, W. H., Mol, A. P. J., & Khaodhair, S. (2006). Options for environmental sustainability of the crude palm oil industry in Thailand through enhancement of industrial ecosystems. *Environment, Development and Sustainability, 8*, 271–287.

Chongkhong, S., Tongurai, C., Chetpattananondh, P., & Bunyakan, C. (2007). Biodiesel production by esterification of palm fatty acid distillate. *Biomass and Bioenergy, 31*(8), 563–568.

Cockerill, S., & Martin, C. (2008). Are biofuels sustainable? The EU perspective. *Biotechnology for Biofuels, 2008*, 1–9.

CONCAWE, EUCAR, & JRC. (2006). Well-to-wheels analysis of future automotive fuels and powertrains in the European context. Well-to-tank report version 2b. European Commission, Brussels.

Corley, R. H. V. (2006). Ten steps towards sustainability of palm oil production. *Announcement within the round table on sustainable palm oil initiative*. http://www.rspo.org/PDF/Main%20page/Ten%20steps%20towards%20increased%20sustainability.pdf. Accessed January 2007.

Corley, R. H. V., & Tinker, P. B. (2003). *The oil palm* (4th ed.). Oxford: Blackwell Publishing.

Department of Environment. (1999). *Industrial processes & the environment (Handbook No. 3)*. Crude Palm Oil Industry. Department of Environment, Malaysia.

European Union (EU). (2009). Directive 2009/28/EC of the European Parliament and of the council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing directives 2001/77/EC and 2003/30/EC. *Official Journal of the European Union, L140*, 16–61.

FAO. (2004). *Fertilizer use by crop in Malaysia*. Food and Agriculture Organization of the United Nations (FAO), Rome. http://www.fao.org/docrep/007/y5797e/y5797e00.htm. Accessed December 2006.

FAO. (2005). *State of the world's forests 2005, Food and Agriculture Organization of the United Nations (FAO)*. Rome: FAO.

FAOSTAT. (2006). *FAOSTAT agriculture data*. Food and Agriculture Organisation of the United Nations (FAO). http://apps.fao.org. Accessed December 2006.

Fargione, J., Hill, J., Tilman, D., Polasky, S., & Hawthorne, P. (2008). Land clearing and the biofuel carbon debt. *Science, 319*, 1235–1238.

Fee, C. G., & Sharma, M. (2002). Integrated pest and disease management and associated impact of pesticides. In G. Singh, L. K. Huan, T. Leng, & D. L. Kow (1999). *Oil palm and the environment – A Malaysian perspective*. Malaysian Oil Palm Growers Council, Kuala Lumpur.

Field, C. B., Campbell, J. E., & Lobell, D. B. (2008). Biomass energy: the scale of the potential resource. *Trends in Ecology & Evolution, 23*, 65.

Frese, S. D., Ibsen, S. R., Bang, J. K., & Andersen, J. (2006). *Madens globale fodaftryk (English: Global footprint of food)*. Copenhagen: WWF Denmark.

Garrity, D. P., Soekardi, M., van Noordwijk, M., de la Cruz, R., Pathak, P. S., Gunasena, H. P. M., et al. (1997). The Imperata grasslands of tropical Asia: area, distribution, and topology. *Agroforestry Systems, 36*, 3–29.

German Advisory Council on Global Change (WBGU). (2008). *World in transition, future bioenergy and sustainable land use, summary for policy-makers*. Berlin: WBGU.

Glastra, R., Wakker, E., & Richert, W. (2002). *Oil palm plantations and deforestation in Indonesia*. What Role Do Europe and Germany Play?. WWF Switzerland, Zurich.

GM, LBST, BP, ExxonMobil, Shell, TotalFinaElf. (2002). *Well-to-wheel analysis of energy use and greenhouse gas emissions of advanced fuel/vehicle systems—A European Study*. L-B Systemtechnik GmbH, Ottobrunn, Germany.

Hansen, A. K. (2006). Personal communication with Anders Kromand Hansen, engineer, AarhusKarlshamn Denmark, Aarhus. In J. H. Schmidt (2007). *Life assessment of rapeseed oil and palm oil. Ph.D. thesis, part 3: Life cycle inventory of rapeseed oil and palm oil*. Diss. Department of Development and Planning, Aalborg University.

Henson, I. E. (2004). *Modelling carbon sequestration and emissions related to oil palm cultivation and associated land use change in Malaysia*. MPOB Technology No. 27, December 2004. Kajang, Malaysia.

Husain, Z., Zainal, Z. A., & Abdullah, M. Z. (2003). Analysis of biomass-residue-based cogeneration system in palm oil mills. *Biomass and Bioenergy, 24*, 117–124.

IFA, IFDC, IPI, PPI, FAO. (2002). *Fertilizer use by crop*. www.fertilizer.org/ifa/statistics/crops/fubc5ed.pdf . Accessed July 2002.

Institut für Energie- und Umweltforschung Heidelberg GmbH (IFEU). (2010). *Sustainable biomass, palm oil GHG calculator IFEU 09-10 vs1.xls*. Heidelberg, Germany.

IPCC. (2003). *Good practice guidance for land use, land-use change and forestry*. Geneva: Intergovernmental Panel on Climate Change (IPCC).

JEC. (2011). Database. http://ies.jrc.ec.europa.eu/jec-research-collaboration/downloads-jec.html. Accessed May 2011.

Kandiah, S., Hasan, M., & Yaacob, M. (1992). Overview of automation in a palm oil mill-the sterilisation process. *Computing and Control Engineering Journal, 3*(1), 45–52.

Kang, L. J. (2006). *Refinery of palm oil. Webpage. ASTS Fellow, Pusat Pengajian Kejuruteraan Kimia di Universiti Sains Malaysia, Kuala Lumpur*. http://www.andrew.cmu.edu/user/jitkangl/Index.htm. Accessed December 2006.

Lim, C. H., Singh, G., & Lim, K. H. (1999). Production of organic fertilisers and soil conditioners. In G. Singh, L. K. Huan, T. Leng, & D. L. Kow (1999). *Oil palm and the environment—A Malaysian perspective*. Malaysian Oil Palm Growers Council, Kuala Lumpur.

Ma, A. N., Choo, Y. M., Toh, T. S., & Chua, N. S. (2004). Renewable energy from palm oil industry. Not published. Updated version of chapter 17. In G. Singh, L. K. Huan, T. Leng, & D. L. Kow (1999). *Oil palm and the environment—A Malaysian perspective*. Malaysian Oil Palm Growers Council, Kuala Lumpur.

Menichetti, E., & Otto, M. (2009). Energy balance and greenhouse gas emissions of biofuels from a life-cycle perspective. Biofuels: Environmental Consequences and Interactions with Changing Land Use. In Proceedings of the Scientific Committee on Problems of the Environment (SCOPE) (2009). International Biofuels Project Rapid Assessment, Gummersbach, pp. 81–109.

Møller, J., Thøgersen, R., Kjeldsen, A. M., Weisberg, M. R., Soegaard, K., Hvelplund, T., et al. (2000). *Fodermiddeltabel—Sammen-sætning og foderværdi af fodermidler til kvæg (English: Feeding component table—Composition and feeding value of feeding components for cattle), Rapport nr 91*. Foulum, Denmark: Landsudvalget for Kvæg.

MPOB. (2005). *Review of the Malaysian Oil Palm Industry 2004*. Economics and Industry Development Division, Malaysian Palm Oil Board, Kelana Jaya.

MPOB. (2006). Review of the Malaysian oil palm industry 2005. Economics and Industry Development Division, Malaysian Palm Oil Board, Kelana Jaya.

Oil World. (2005). Oil world annual 2005. www.oilworld.biz. Accessed December 2005.

Pagiola, S. (2000). *Land use change in Indonesia*. Washington, DC: World Bank Environment Department.

Pehnelt, G., & Vietze, C. (2009). European policies towards palm oil—sorting out some facts. *Jena Economic Research Paper, 2009*(086), 1–30.

Pleanjai, S., Gheewala, S. H., & Garivait, S. (2007). Environmental evaluation of biodiesel production from palm oil in a life cycle perspective. *Asian Journal of Energy and Environment, 8*, 15–32.

PortWorld Distances. (2011). Distance calculation. http://www.portworld.com/map. Accessed May 2011.

ProForest. (2003). *Palm oil forests and sustainability—Discussion paper for the round table on sustainable palm oil.* ProForest, Oxford, United Kingdom.

Schmidt, J. H. (2007). *Life assessment of rapeseed oil and palm oil. Ph.D. thesis, part 3: Life cycle inventory of rapeseed oil and palm oil*. Diss. Department of Development and Planning, Aalborg University.

Schmidt, J. H. (2008). System delimitation in agricultural consequential LCA, outline of methodology and illustrative case study of wheat in Denmark. *International Journal of Life Cycle Assessment, 13*(4), 350–364.

Schmidt, J. H., & Weidema, B. P. (2008). Shift in the marginal supply of vegetable oil. *International Journal of Life Cycle Assessment, 13*(3), 235–239.

Silva, C. M., Goncalves, G. A., Farias, T. L., & Mendes-Lopes, J. M. C. (2006). A tank-to-wheel analysis tool for energy and emissions studies in road vehicles. *Science of the Total Environment, 367*, 441–447.

Singh, G. (1999). The Malaysian oil palm industry: Progress towards zero waste and environment excellence. *Bioresources Technology for Sustainable Agriculture, 99*, 318–341.

Singh, G. (2006). Personal communication with director of research gurmit singh, United Plantations Berhad, Research Department, Jendarata Estate, Teluk Intan, Malaysia. In J. H. Schmidt (2007). *Life assessment of rapeseed oil and palm oil. Ph.D. thesis, part 3: Life cycle inventory of rapeseed oil and palm oil*. Diss. Department of Development and Planning, Aalborg University.

Singh, G., Kow, D. L., Lee, K. H., Lim, K. C., & Loong, S. G. (1999). Empty fruit bunches as mulch. In G. Singh, L. K. Huan, T. Leng, D. L. Kow (1999) *Oil palm and the environment—A Malaysian perspective*. Malaysian Oil Palm Growers Council, Kuala Lumpur.

Singh, G., & Thorairaj, I. N. P. (2006) Data on energy use in the oil mill. Data provided by research director Gurmit Singh and process engineer Ir. NP Thorairaj, United Plantations Research Department, Teluk Intan, Malaysia. In J. H. Schmidt (2007). *Life assessment of rapeseed oil and palm oil. Ph.D. thesis, part 3: Life cycle inventory of rapeseed oil and palm oil*. Diss. Department of Development and Planning, Aalborg University.

Subranamiam, V. (2006a). Personal communication with Vijaya Subramaniam, Energy and Environment Unit, Malaysian Palm Oil Board (MPOB), Kajang. In J. H. Schmidt (2007). *Life assessment of rapeseed oil and palm oil. Ph.D. thesis, part 3: Life cycle inventory of rapeseed oil and palm oil*. Diss. Department of Development and Planning, Aalborg University.

Subranamiam, V. (2006b). Life cycle inventory for palm kernel crushing. Unpublished data by research officer Vijaya Subramaniam, Energy and Environment Unit, Malaysian Palm Oil Board (MPOB), Kajang. In J. H. Schmidt (2007). *Life assessment of rapeseed oil and palm oil. Ph.D. thesis, part 3: Life cycle inventory of rapeseed oil and palm oil*. Diss. Department of Development and Planning, Aalborg University.

Subranamiam, V., Chow, M. C., & Ma, A. N. (2004). *Energy database of the oil palm. Palm oil engineering bulletin, Volume EB70*. Malaysian Palm Oil Board (MPOB), Kajang.

Subranamiam, V., Ma, A. N., & Choo, Y. M. (2005). *Life cycle inventory of the production of CPO*. Poster presentation at PIPOC 2005, 25–29 September, Kuala Lumpur.

Suppalakpanya, K., Ratanawilai, S. B., & Tongurai, C. (2010). Production of ethyl ester from esterified crude palm oil by microwave with dry washing by bleaching earth. *Applied Energy, 87*, 2356–2359.

Teoh, C. H. (2000). *Land use and the oil palm industry in Malaysia: Report of WWF Malaysia*. Selangor, Malaysia: WWF Malaysia.

Tilman, D., Hill, J., & Lehman, C. (2006). Carbon-negative biofuels from low-input high-diversity grassland. *Biomass Science, 314*, 1598–1600.

Unilever. (1990). LCI datasheets for palm oil, palm kernel oil and coconut oil. Provided by Peter Shonfield 2004, Unilever (not published). In J. H. Schmidt (2007). *Life assessment of rapeseed oil and palm oil. Ph.D. thesis, part 3: Life cycle inventory of rapeseed oil and palm oil*. Diss. Department of Development and Planning, Aalborg University.

United Plantations Berhad (UPB). (2006). *Annual report 2005*. Teluk Intan, Malaysia: United Plantations Berhad.

UPRD. (2004). *Environmental impact assessment of oil palm cultivation and processing in united plantations berhad*. Teluk Intan, Malaysia: United Plantations Research Department, United Plantations Berhad.

U.S. Energy Information Administration. (2011). *International energy statistics, biofuels production*. http://tonto.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=79&pid=79&aid=1. Accessed May 2011.

Wakker, E. (2004). *Greasy palms—The social and ecological impacts of large-scale oil palm plantation development in Southeast Asia*. London: Friends of the Earth United Kingdom.

Weidema, B. (2001). Avoiding co-product allocation in life-cycle assessment. *Journal of Industrial Ecology, 4*(3), 11–33.

Weindorf, W. (2008). *Vergleichende betrachtung der Herstellung von Biodiesel und im Co-Processing hydrierten Pflanzenölen*. Ottobrunn, Germany: Ludwig-Bölkow-Systemtechnik GmbH.

Weng, C. K. (1999). Biomass production in the oil palm industry. In G. Singh, L. K. Huan, T. Leng, D. L. Kow (1999) *Oil palm and the environment—A Malaysian perspective*. Malaysian Oil Palm Growers Council, Kuala Lumpur.

Yacob, S., Hassan, M. A., Shirai, Y., Wakisaka, M., & Subash, S. (2006). Baseline study of methane emission from anaerobic ponds of palm oil mill effluent treatment. *Science of the Total Environment, 366*, 187–196.

Yusof, B., & Weng, C. K. (2004). The oil palm and its sustainability. *Journal of Palm Oil Research, 16*(1), 1–10.

Yusoff, S. (2006). Renewable energy from palm oil—innovation on effective utilization of waste. *Journal of Cleaner Production, 14*, 87–93.

Yusoff, S., & Hansen, S. B. (2007). Feasibility study of performing a life cycle assessment on crude palm oil production in Malaysia. *International Journal of Life Cycle Assessment, 12*(1), 50–58.