JENA ECONOMIC RESEARCH PAPERS

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by

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Abstract

During the last years, the renewable energy strategy of the European Union (EU) and the proposed policies and regulations, namely the Renewable Energy Directive (RED), have been heavily discussed among scientific circles and various interest groups. The sustainability of different biofuels and their contribution to the reduction of greenhouse gas (GHG) emissions and the whole renewable strategy has become one of the most controversial issues.

RED requires that the greenhouse gas emissions associated with production and use of biofuels are at least 35% lower than those associated with the production and use of conventional fuels to be classified as 'sustainable' and therefore eligible for the mandatory blending scheme applied within the EU.

In a recent working paper, we analyze the GHG emissions savings potential of rapeseed biodiesel. For this purpose, the we ran a life cycle assessment of rapeseed biodiesel using the same basic methodology and background data contained in RED by considering the whole production chain from cultivation of the feedstock up to use of the biofuels. Unlike other studies, we refer only to publicly available and published data in our calculations. In order to ensure full transparency – again contrary to the vast majority of other studies – we provide a detailed documentation of all data. We follow a rather conservative approach by using average values and assuming common conditions along the supply chain in their scenarios.

In most of the scenarios, rapeseed biodiesel does not reach the GHG emissions saving values using the formula contained in RED. Neither the RED typical value for rapeseed oil (45%) nor even the lower default value (38%) can be supported by the analysis. Furthermore, most of the scenarios indicate that rapeseed biodiesel does not reach the 35% threshold required by the EU Directive for being considered as sustainable biofuel. In the standard scenario, we calculate a GHG emissions saving value of not even 30% which is not only well below the GHG emissions saving values (default and typical) that can be found in RED but also far below the 35% threshold.

To summarize, we are not able to reproduce the GHG emissions saving values published in the annex of RED. Therefore, the GHG emissions saving values of rapeseed biodiesel stated by the EU are more than questionable. Given these striking differences as well as the lack of transparency in the EU's calculations, we assume that the EU seems to prefer 'politically' achieved typical and default values regarding rapeseed biodiesel over scientifically proven ones.

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1.   Introduction

During the last couple of years, the renewable energy strategy of the European Union (EU) and the proposed policies and regulations, namely the Renewable Energy Directive (RED), have been heavily discussed among scientific circles, by various interest groups and other more or less involved players. With respect to the EU's strategy and policies regarding the transportation sector, biofuels have become one of the most controversial issues. The 'sustainability' of different biofuels and their contribution to the reduction of greenhouse gas (GHG) emissions and the whole renewable strategy has been challenged.

RED requires that the greenhouse gas emissions associated with production and use of biofuels are at least 35% lower than those associated with the production and use of conventional fuels to be classified as 'sustainable' and therefore eligible for the mandatory blending scheme applied within the EU.

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 needs to be considered. Consequently, the EU assesses the sustainability of different biofuels based on so-called Life Cycle Assessments (LCA) of the total GHG emissions – and savings – of these biofuels. However, as shown in previous papers (Pehnelt and Vietze 2009; Pehnelt and Vietze 2011) and has been found by related studies, the GHG emissions saving values published in the annex of RED are, firstly, rather questionable and, secondly, latently discriminatory against biofuels from non-European sources due to the adverse application of so-called 'typical' and 'default' values. Methodological drawbacks and especially the lack of transparency in the underlying data and calculation methods have caused a lively discussion and various disputes between different interest groups and EU officials.

Rapeseed is by far the most important source of biodiesel produced in the European Union and has experienced dramatic growth rates since the introduction of various national support schemes, not least prompted by the RED. In this paper, we recalculate the GHG emissions saving potential of rapeseed biodiesel based on the background data provided by the EU and realistic assumptions and data from the rapeseed biodiesel production. We are using the same methodology used in a previous paper on palm oil biodiesel (see Pehnelt and Vietze 2011) and adjust the background data and scenarios to the common conditions and supply chains of rapeseed biodiesel production in Europe.

Our results indicate that the 'sustainability' of rapeseed biodiesel in the interpretation of RED is at best very questionable, and in most scenarios simply unjustifiable. We are not able to reproduce the GHG emissions saving values published in RED for rapeseed biodiesel. In most of our scenarios, rapeseed biodiesel not only shows a considerably inferior GHG emissions saving performance than proposed by RED but also fails outright to reach the 35% threshold in 8 out of 12 scenarios considered. Thus, the question of whether rapeseed is a sustainable source of biodiesel can be answered as follows: as with all scientific assessment, it depends on the specific conditions and production technologies, but the overall evidence points towards answering the question in the negative. It is extremely likely that European rapeseed biodiesel does not, in fact, meet the current EU definition of sustainability.

2.   Methodology

In order to calculate the GHG impact of rape oil, we conduct a life cycle analysis including all activities associated with the plantation, conversion, transport and use of this biofuel. The methodology of the calculation scheme is laid down in part C Annex V of the Directive 2009/28/EC and in Annex IV © of Directive 2009/30/EC (land use change). As in the EU (2009) Directive Annex V (C), GHG emissions reductions are calculated as follows:

$$SAVING = (E_F - E_B)/E_F;$$

where E_B is the total emission from the respective biofuel and E_F is the total emission 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 = annualized emissions from carbon stock changes caused by 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 CO2-emission values for the GHG emission savings. We consider the case of rapeseed oil fuel – produced in Europe – compared with fuel from crude oil. Using the same basic calculation scheme as in a previous paper on palm oil (Pehnelt and Vietze 2011), we derive a realistic default value for rapeseed oil diesel by using current input and output data of biofuel production and documenting all background data, inputs and outputs as well as every single step in detail.

We calculate two different scenarios each with three different esterification values. Reliable and well-documented data on the production conditions (and the relevant emission values during the production chain) of rapeseed oil diesel are used.

The production of rapeseed oil is divided into five stages: agricultural stage, oil mill stage, refinery stage, transport stage and esterification stage. The transport stage includes the transport of refined oil from the refinery or biodiesel from the esterification plant to final use. To allow for comparability with other biofuels from overseas, the final port is assumed to be represented by the Port of Rotterdam. Except for transportation associated with the collection of harvested rapeseed to the mill, we do not account for any further transportation. As – according to the EU-Directive (EU 2009, Annex V, C Methodology) – CO_2 emissions from the manufacture of machinery and equipment shall not be taken into account, we do not consider the emissions from overhead (operation of buildings, administration, marketing etc.) and capital goods (building, machinery and means of transportation) in our LCA.

The description of the production process is based on Schmidt (2007) (plantation, milling, and refinery) and van Gerpen (2005) and Ma and Hanna (1999) (esterification). The determination of the system boundaries is based on the methodology presented in Schmidt and Weidema (2008) (milling, refinery); Schmidt (2008) (plantation) and van Gerpen (2005) (esterification).

We use a realistic baseline model to calculate GHG emissions for every step of the rapeseed diesel production chain based on the background data provided by the latest available version of the JEC (2011) database.[1] Furthermore, the input and output data is sourced on the average of realistic values published in reliable scientific studies.

Specific calculation tools provided by IFEU (2011) and based on the Intelligent Energy Europe (IEE) project BioGrace (2010) are used in this paper. These tools are engineered to produce greenhouse gas (GHG) calculations using the methodology as given in the Directives 2009/28/EC (Renewable Energy Directive) and 2009/30/EC (Fuel Quality Directive).

In contrast to the EU-Directive (EU 2009) as well as quite a few other studies we provide full transparency by indicating all input and output data, assumptions, methodology and background data. Furthermore, we do not use unrealistically favorable assumptions on the conditions and supply chains but rely only on well documented precise measured and proven primary and secondary data instead.

Pehnelt and Vietze (2009) address the problems of direct and indirect land use change. They find a lot of uncertainties and vague and biased assumptions regarding the measurement of these effects. Many environmental organizations lobby for this issue (e.g. Frese et al. 2006, Casson 2003, Wakker 2004), but even the EU (2009) themselves accept these problems, as they do not account for land use change in calculating biofuel default values. Thus, following the EU-Directive (EU 2009) methodology to calculate default values, we do not consider the problem of land use change – be it direct or indirect – in this paper. As our aim is a realistic, reliable and scientifically founded approach, we focus on GHG emissions related to plantation, processing and transport of rape biodiesel, as only these steps are free of uncertainties regarding the reasons and effects of GHG emissions.

Furthermore, the issue of land use change (as well as biodiversity) is addressed by explicit sustainability criteria given in EU (2009) and should be considered separately from the GHG emissions saving potential. It is an explicit requirement of RED that there should be no damages to sensitive, important or carbon rich ecosystems while cultivating energy

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

feedstocks for biofuels (EU 2009, Preamble, 69 ff). This requirement has the ambition to prevent a situation where biofuels will be sourced through the replacement of virgin rainforest, wetland, peatlands or protected areas. It limits biofuels 'made from raw materials obtained from land with high biodiversity value' defined in the following as 'primary forest […] highly biodiverse grassland … [and] areas designated by law or by the relevant competent authority for nature protection purposes' (EU 2009, Article 17, 3). Moreover, biofuels made from crops from land with 'a high carbon stock' such as 'wetlands […] continuously forested areas […] land spanning more than one hectare with trees higher than five metres and a canopy cover of between 10 % and 30 %, or trees able to reach those thresholds in situ … [and] … peatlands' EU (EU 2009, Article 17, 4) are also deemed as 'unsustainable' within the RED legal terminology. Although these definitions lack in certainty and clarity (which is criticized in an earlier paper (see Pehnelt and Vietze 2009)), it can be said that the current EU regulation on biofuels takes possible negative side-effects associated with the plantation of biofuel crops into account. Thus, a calculation tool for land use change – especially if such land use change is supposed to occur indirectly via very complex global processes – is not needed here.

3.   Calculation of GHG Emissions (Saving) of Rapeseed Biodiesel

3.1 Plantation

According to the United States Department of Agriculture (USDA 2011), rapeseed was the third leading source of vegetable oil in the world in 2011, after palm oil and soybean oil. Oilseed rape is the only indigenous oil crop that is used to produce commercial biodiesel in the EU and is by far the most important source of biofuel produced in Europe. Rape for oilseed may be grown either as winter rape (between October and following August) or as spring rape (between March and September). As the plant has a longer period to grow in the spring time, winter rape provides better yields compared to spring oilseed (Thamsiriroj and Murphy 2009). It is agricultural standard that the rape seed portion is the only valuable harvested component of the crop. Although the straw could be used for cattle feed or as input to other bioenergy plants, typically, it is ploughed back into the land as an organic fertilizer and – therefore – reduces the N-fertilizer requirement for subsequent crops planted on the very field (see N-fertilizer credit below). The rape plant (Brassica napus) grows to a height of approximately 140 cm and the rapeseeds contain around 44% oil and 23% protein (Møller et al. 2000, Dansk Landbrugsrådgivning 2007). It grows on clay as well as on sandy soils. Rape is an annual crop and is not self-compatible; the entire rape plantation cannot replant with rape the following 2-3 years (Lehuger et al. 2011). Schmidt (2007) recommends at least four years between two rapeseed crops to avoid fungus attacks.

Normally there are 50-100 plants per square meter. Before sowing, the soil must be ploughed, compacted and sprayed with herbicides to control weeds. The seeds are normally treated with pesticides to avoid pest attack during seed germination. Winter rapeseed is sown in August and spring rape-seed is sown at the beginning of April. Weeding of the rows between the rapeseed plants are typically done twice during the growing period and later by applying several different herbicides and insecticides.[2]

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[2]   For more details see for instance Dansk Landbrugsrådgivning (2005a, 2005b).

Harvesting typically takes place in July for winter rapeseed and in late August for spring rapeseed. Harvesting is done mechanically by a conventional harvester (Schmidt 2007).

The inventory data of the agricultural stage includes activities related to cultivation of rapeseed. Due to excellent data availability on the micro level, we take the inventory data based on Danish data from 2002 to 2005 on the average production of conventional rapeseed (1% spring rape and 99% winter rape) according to Schmidt (2007). The product flow of the cultivation is based on data from Statistics Denmark (Danmarks Statistik 2012) and Dansk Landbrugsrådgivning (2005a, 2005b). 5 kg seed/ha is needed in order to achieve the desired plant density (Dansk Landbrugsrådgivning 2005a). According to Nemecek et al. (2003), seed production requires 75% more land to produce seed for seeding than conventional rapeseed. Therefore, the use of 5 kg seed requires the intervention value as the cultivation of around 9 kg conventional rapeseed (Schmidt 2007). Yields are obtained from FAOSTAT (2012). We apply the EU's average 1991-2005 of 2781.3 kg oilseed yield per ha per year.[3] After drying (according to Jensen et al. (2005), water content in rapeseed is dried 3 %) we use a value of 2781.3 kg x 0.97 = 2697.9 kg dried oilseed yield per ha per year. Nemecek et al. (2003) and Dalgaard et al. (2001) estimate the electric energy consumption related to drying of 1 percentage point of 1 kg crop with 96 KJ and 50 KJ respectively. We use the average of 73 KJ. As started above, he yield from one hectare is 2781.3 kg undried rapeseed. Since the rapeseed is dried 3 percentage points, this corresponds to an energy use of (73 KJ x 3 x 2781.3 kg = 609104.7 KJ) = 169.2 kWh electricity per ha per year (or 169.2 kWh / 2.781 t = 60.83 kWh per t rapeseed).

A further source of CO_2 emissions for field work stems from fossil diesel for field works and transport. Energy demand for miscellaneous transport (passenger car), e.g. inspection of field, equal to 6.1 liter diesel/ha (Dalgaard 2007). According to Schmidt (2007), the total average diesel consumption for traction can be calculated as 3860 MJ/ha/a = 106 l diesel per hectare per year.[4] The calculation takes 41% sand and 59% clay soils (which require different field work intensities) as basis (Danish Institute for Agricultural Science 2005). The calculated value for diesel consumption is based on the average of reported data by Nemecek et al. (2003), Dalgaard et al. (2001) and Dalgaard et al. (2006); the number of field work processes is the average value obtained from Nemecek et al. (2003), Dalgaard et al. (2001), Dalgaard et al. (2006), Dansk Landbrugsrådgivning (2005a), and Jensen et al. (2005). Thus, the total value for miscellaneous transport and traction accounted for by 112.1 l diesel per ha per year.

The major emission source of plantation relates to fertilizers. The need for nitrogen fertilizers depends on the crop (winter/spring rapeseed), the soil type, the previous crop and application of manure. Other fertilizers include phosphorus (P_2O_5), potassium (K_2O); and in most cases lime (CaO) to reduce the soil acidity (Thamsiriroj and Murphy 2010).

Using the appropriate plantation scheme according to Jacobsen et al. (2002) and norms for yield and application of N-fertilizers by Plantedirektoratet (2005), Schmidt (2007) calculates that 140 kg N per ha per year is applied to rapeseed. In reality, the requirement of N-fertilizers is higher: 140 kg + 27 kg ('previous-crop'-value) = 167 Kg N/ha is applied, but 27

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[3]   According to Jensen et al. (2005) 87% of the straw is left in the field. It is currently uncommon to utilize it for energy purposes.
[4]   The value for energy content of fossil diesel is obtained from Andersen et al. (1981).

kg N/ha can be saved for the crop after rapeseed, as crop rotation is needed. Therefore, the 27 kg N/ha should be credited to rapeseed (see Hvid et al. 2004).

We use the same calculation methodology as in RED (EU 2009) and – therefore – the RED values for NOx field emissions.[5] The application of P-fertilizer and K-fertilizer is determined from the soil's P- and K-value. We use the application values from Schmidt (2007) based on average numbers given in Dansk Landbrugsrådgivning (2005a, 2005b) of 25 kg P-fertilizer (which corresponds to 57 kg P2O5) and 82 kg K-fertilizer (which corresponds to 99 kg K2O) per ha per year. In the second scenario we rely on the more realistic case of lime (CaO) application of 2000 kg per hectare per year to reduce the soil acidity (Thamsiriroj and Murphy 2010). The data on pesticide use in rapeseed cultivation is based on Dalgaard (2007) and Dalgaard et al. (2008). They estimate a (relatively low) value of 0.84 kg per ha per year (which equal 0.27 kg/ha/a active ingredient) total pesticides application. Given the energy and fertilizer intensity, it can be said that rapeseed is a high-energy input crop as the land must be ploughed, the seeds sown and the land fertilized every year (see Thamsiriroj and Murphy (2009) among others).

3.2 Milling

For the rapeseed milling process we use data according to Schmidt (2007). The production process and inventory data (from 2003 and 2004) are based on rapeseed oil milling at AarhusKarlshamn in Aarhus, Denmark (Aarhus United 2005a, 2005b; Kronborg 2006 and Hansen 2006). Additionally, we use specifications given by Korning (2006), Kronborg (2006), Hansen (2006) and Bockisch (1998).

Two different types of oil mill technologies exist; solvent extraction and mechanical pressing. The solvent extraction is the most dominant technology in the rapeseed oil industry in order to achieve a higher oil extraction rate (Bockisch 1998, Kronborg 2006, Schmidt 2007). The milling process includes rapeseed reception, storage, screening, pre-heating, rolling and heat treatment. Following, the seeds are pressed which gains crude rapeseed oil (RSO) (ca. 42 % of total oil output) and rapeseed (RS) cake (or RS meal). After that, the flakes from the press process are sent to solvent extraction. In the extraction process an extraction solvent is used.

According to Bockisch (1998), hexane is the most dominant solvent used. The consumption of hexane per tonne pressed and extracted rapeseed oil output is 1.188 kg or (1.188 kg x 0.4189 =) 0.498 kg hexane per t rapeseed input (Kronborg 2006). The solvent extraction produces two outputs; extraction cake and miscella. The hexane effuse from the cake and it is finished after drying. Miscella is a mix of solvent (hexane) (ca. 70-90%) and oil (ca.10-30%). The solvent should be removed and reused. However, effuse losses occur. The oil is clarified and centrifuged to gain the second fraction of crude oil (58 % of total oil output). The

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[5] Crutzen et al. (2007) estimate far higher CO2eq emissions from N2O entering the atmosphere as a result of using N-fertilizers to produce crops for biofuels than that estimated on the basis of IPCC (2006). By comparing the N2O emission from biofuel production with emissions from fossil fuel, they find that the production of commonly used biofuels, especially biodiesel from rapeseed and bioethanol from corn, can contribute as much or more to global warming than savings by fossil fuel replacement. Crops with less N demand, such as woody coppice species (e.g. oil palm) have more favourable climate impacts (Crutzen et al. 2007). Malça and Freire (2011) find that GHG emissions do completely offset carbon gains attributed to rapeseed oil production for several decades if grassland is conversed into rape plantation. Reason is a far higher N-fertilizer requirement, and therefore higher N2O field emissions, of such plantations.

residual from the centrifugation is lecithin which – in general – is fed into the rapeseed meal fraction (Korning 2006, Schmidt 2007). Thus, it is not treated as a by-product.

According to Aarhus United (2005a, 2005b) the output of 1000 t rapeseed equals 418.9 t crude RSO and 563.8 t RS cake. The RS cake contains a residual of 4% oil (Møller et al. 2000). This residual oil will be credited to the input/output ratio (added to the oil output) as it is used as animal fodder in the rapeseed cake. Based on Oil World (2005), the average overall loss (from screening, transport, and waste water) of rapeseed in oil mills is accounted by 1.7%. Normally, rapeseed is transported by truck to the oil mill. Schmidt (2007) estimates an average transport distance from several plantation suppliers in Europe of around 100 km.

According to Kronborg (2006) and Aarhus United (2005b), energy consumption related to both pressing and extraction is 1586 MJ heat and 419 MJ electricity from the grid per tonne of rapeseed oil. In most cases, the production of heat (steam) is done with cogeneration from fossil fuel oil (same heating value as diesel). According to Schmidt (2007), 1.145 MJ fuel oil is used to produce 1 MJ heat and 0.057 MJ electricity as surplus electricity (sources on energy efficiency: Energistyrelsen 1995, Aarhus United 2004, 2005b). The surplus electricity is credited to the electricity from grid. Using the lower heating value of 35.86 MJ/l from JEC E3-database (EU 2009) the input of processing steam for the production of 1 t RSO is (1586 MJ heat x 1.145 MJ =) 1816.0 MJ diesel = 50.64 l diesel and (1586 MJ heat x -0.057 MJ surplus electricity =) -90.4 MJ (surplus electricity). Crediting the surplus electricity, the required electricity from grid is (419 MJ – 90.4 MJ =) 328.6 MJ per t RSO. Thus, (49.89 l x 0.4189 =) 21.21 l diesel (light oil) and (328.6 MJ x 0.4189 =) 137.65 MJ = 38.236 kWh electric energy from grid is used to process an input of 1 t rapeseed.

Moreover we have to add the additional emissions of hexane related to the solvent extraction process. According to Schmidt (2007), three sources of hexane emission are related to production of crude rapeseed oil: extraction, processing of rapeseed cake and from storage tanks. In Europe, the hexane emissions from extraction can be considered as nearly zero, as the exhaust gas from the extraction is sent to the power central where it is used as input air to the burning of fuel oil. Hereby, the hexane is converted into water and carbon dioxide (Aarhus United 2005a). However, a considerable share of the input of hexane goes with the rapeseed cake to final processing. By using values from Aarhus United (2005a), Schmidt (2007) calculates the hexane emission related to the processing of rapeseed cake as 0.63 kg per tonne crude rapeseed oil. As mentioned above, the consumption of hexane per tonne rapeseed oil is 1.188 kg. Aarhus United (2005a) states that there is a hexane emission from storage tanks of 46 g per kg hexane used. Thus, the emission from storage tanks are 0.055 kg per tonne produced rapeseed oil and, therefore, the total emission of hexane from extraction is 0.69 kg per tonne crude rapeseed oil or (0.69 kg x 0.4189 =) 0,289 kg per tonne rapeseed input.

Hexane (C_6H_{14}) is a so-called Non-Methane Volatile Organic Compound (NMVOC) and has an indirect greenhouse warming potential (GWP) higher than CO_2. According to the IPCC (2007) indirect effects 'include the direct effects of degradation products or the radiative effects of changes in concentrations of greenhouse gases caused by the presence of the emitted gas or its degradation products. Collins et al. (2002) calculates indirect GWPs for 10 NMVOCs with a global three-dimensional Lagrangian chemistry-transport model. Unfortunately, the CO2eq related to hexane is not assessed currently. However, the indirect

GWP values of similar NMVOCs (e.g. Ethane, Propane, and Butane) do not differ to a great extent, so that we – similar to the IPCC (2007) – rely on these values:

Weighting the GWPs of NMVOC according to Collins et al. (2002) gives a weighted average 100-year GWP of 7.4 CO2eq.[6] Following the approach taken by the IPCC (2007), the CO2 produced from oxidation of NMVOCs (direct GWP) is not included in the GWP estimates since this carbon should be included in the national CO2 inventories and – therefore – is included in our inventory data of used hexane in the oil milling process. Subtracting the average GWP for the radiative forcing mechanism involving CO2 (3 CO2eq), the IPCC (2007) gets an average GWP for NMVOCs of 3.4 CO2eq. Thus, we calculate a scenario adding greenhouse gas emissions related to the milling process of (690 g hexane emissions per tonne crude rapeseed oil x 3.4 CO2eq/hexane) 2.346 kg CO2eq per t crude RSO in our LCA.

3.3   Refining

The refining process includes neutralization, bleaching and deodorization of the oil. The output of the refinery is refined rapeseed oil (RefRSO). The inventory in this section is based on chemical refining which is the most widespread method for refining. The description and inventory values are based on Schmidt (2007), Hansen (2006) and Bockisch (1998).

The purpose of neutralisation (and degumming) is to remove lecithin and free fatty acids. The lecithin is removed by applying phosphoric acid; while the content of free fatty acids is removed by applying sodium hydroxide. The reaction outcome of sodium hydroxide with the free fatty acids is soap and water. Following, the soap is separated via a centrifuge and is sent through the soap stock splitting process. Here, sulphuric acid is applied and the outcome is free fatty acids (used as fodder) and sodium sulphate (waste water) (Schmidt 2007). As (the small amounts of) phosphoric acid, sodium hydroxide, and sulphuric acid are mainly used in the production of the by-product animal food, similar to IFEU (2011), we neglect these chemicals as input factors (Pehnelt and Vietze 2011). According to Schmidt (2007) and Hansen (2006), the total oil loss in the neutralization process can be calculated with 1.1%. In the bleaching process, the oil is brought in contact with surface-active substances to remove undesired colored particles and substances. The agent for filtering the oil is bleaching earth (Fullers earth). In the bleaching process, the consumption of bleaching earth amounts to 9.0 kg per t RefRSO output (Hansen 2006). Thus, per 1000 t RSO input (9000 kg x 0.9833 =) 8.85 t bleaching earth is used. Schmidt (2007) estimates a 0.5% loss of oil to the bleaching earth. Finally, to remove undesired odoriferous or flavoring compounds the oil is sent through the deodorization process. In this process, minor amounts of different chemicals are applied, e.g. citric acid, ascorbyl palmitate and A and D vitamins.

Since these ancillaries constitute insignificant amounts (20 gram per ton of RefRSO), they are omitted in this study. In the deodorization process 0.1% of the oil is lost (to the free fatty acids) (Hansen 2006). Thus, according to Schmidt (2007) and Hansen (2006), the output can be calculated with 983.3 t RefRSO per 1000 t input RSO. At this stage, it is assumed that refineries are attached (or nearby) to oil mills. Thus no transport requirements of crude RSO to the refinery is applied (Schmidt 2007).

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[6]   Unfortunately, significant inherent uncertainties may occur by calculation the GWP of NMVOCs.

Energy consumption of refining is 226 MJ heat (steam) and 104 MJ electricity from grid per tonne of RefRSO (Schmidt 2007, Hansen 2006). Assuming the production of heat (steam) is achieved with cogeneration, Schmidt (2007) calculates that 1.145 MJ fuel fossil oil (diesel) is used to produce 1 MJ heat and 0.057 MJ electricity as surplus electricity (sources on energy efficiency: Energistyrelsen 1995, Aarhus United 2004, 2005b). The surplus electricity is credited to the electricity from grid. Using the lower heating value of 35.86 MJ/l according to JEC E3-database (EU 2009) the input of processing steam to the production of 1 t RefRSO is (226 MJ heat x 1.145 MJ =) 258.8 MJ diesel = 7.22 l diesel and (226 MJ heat x -0.057 MJ surplus electricity =) -12.9 MJ (surplus electricity). The required electricity from grid is (104 MJ – 12.9 MJ =) 91.1 MJ per t RefRSO by crediting the surplus electricity. Thus, (7.11 l x 0.9833 =) 7.10 l diesel (light oil) and (91.1 MJ x 0.9833 =) 89.57 MJ = 24.88kwh electric energy from grid is used to process an input of 1 t RSO.

3.4   Transport

The refined rapeseed oil is then transported to final consumption for (co-generated) electricity production in Europe or further processing to FAME / biodiesel (Schmidt 2007). In order to achieve comparability to energy crops from overseas, according to Pehnelt and Vietze (2011), we calculate the transport stage from the refinery (in mid- or northern Europe) to the main fuel port of the EU. The refined rapeseed oil produced in the EU is supposed to be transported in a diesel truck for about 830 km from Denmark (Aarhus) to Rotterdam in the Netherlands (Falk 2012). This is a realistic assumption, as rapeseed is mostly produced in Northern and Eastern Europe while esterification plants are usually situated in big ports. Moreover, it should be noted that we include no other transport emissions in our LCA (e.g. transport from oil mill to refinery) except for collecting the rapeseed from plantations.

3.5   Esterification

In order to convert refined rapeseed oil into biodiesel, which can be used by almost all conventional diesel engines in cars, usually a catalyst transesterification reaction comes into play. This refining method uses an industrial alcohol (methanol in case of RSO because of its low cost and its physical and chemical advantages (polar and shortest chain alcohol) (Ma and Hanna 1999)) and catalysts (bases) to convert the oil into a Fatty-Acid Methyl-Ester (FAME) fuel (US EPA 2009). This process usually requires two to three stages. The refined (and bleached and deodorized) rapeseed oil is thoroughly mixed with methanol and a catalyst (alkali or acid). Alkali-catalyzed transesterification is much faster than acid-catalyzed (Ma and Hanna 1999, Freedman et al. 1984). However if a glyceride has a higher free fatty acid content or more water, acid-catalyzed transesterification is suitable (Sprules and Price 1950, Freedman et al. 1984).

The acids could be phosphoric acid or hydrochloric acid. Sodium hydroxide is the most used Alkali (Sprules and Price, 1950, Ma and Hanna 1999). Alcohol, catalyst, and oil are combined in a reactor and passing through the heater for approximately 1 h at 60 °C. After that, the products were neutralized. Acid (phosphoric acid or hydrochloric acid) is added to the biodiesel to neutralize any residual catalyst and to split any soap that may have formed during the reaction (van Gerpen 2005). The esters and glycerine were continuously separated in the lower chamber of the reactor into two layers.

Further conversion of the methyl ester takes place in a second and sometimes third reactor. The remaining methanol is typically removed after the biodiesel and glycerine have been separated, to prevent the reaction from reversing itself. Glycerine is separated by gravitational settling or centrifuging (Ma and Hanna 1999). The glycerine can then be used in the making of other products, such as soap (REA 2012). Although the economic value of glycerine is higher than its calorific value (see Pehnelt and Vietze 2011), in the following we only consider the energy content of this by-product in calculating the GHG emissions of the whole process. The excess methanol is cleaned and recycled back to the beginning of the process. Once separated from the glycerine, the FAME goes through a clean-up or purification process to remove excess alcohol, residual catalyst and soaps (Pehnelt and Vietze 2011).

Based on the standard methodology proposed by the EU (2009) (Directives 2009/28/EC and 2009/30/EC), we calculate the GHG emissions that can be expected in the transesterification process. We rely on the values according to the EU (2009) as published in IFEU (2011): They use an (energy content weighted) input/output efficiency ratio of 98.8 per cent, a glycerine output of 104.36 kg per t RefRSO and 151.19 kg Methanol; 2.35 kg H_3PO_4; 27.67 kg HCl; 3.46 kg Na_2CO_3; 9.30 kg NaOH in each case per 1000 t RefRSO per year as input factors. To run the reaction, 1141314 kWh natural gas and 62050 kWh electricity from grid per 1000 t RefRSO / year energy is needed.

Alternatively, we derive a second and a third scenario of the esterification process in some of our calculations. These values rely on more current technologies, resulting in lower GHG emissions. We use the same values regarding WTT Appendix 1 (v3) and Weindorf (2008) respectively as displayed in Pehnelt and Vietze (2011) in order to make the emission values of palm oil versus rapeseed oil comparable. Regarding WTT, this denotes an input/output efficiency ratio of 96.44 per cent; a by-product output of glycerine 101.26 kg per t RefRSO; and an input of 106.36 kg Methanol; 1.79 kg H_3PO_4; 19.73 kg HCl; 2.44 kg Na_2CO_3; 6.64 kg NaOH; 825102 kWh natural gas; and 71748 kWh electricity from grid; all per 1000 t RefRSO / year. In a third esterification scenario, according to Weindorf (2008), the value of 7.1 g CO_2eq/MJ FAME is applied for the whole esterification step.[7] Thus, our estimations concerning rapeseed oil are completely comparable to the estimations with regard to palm oil in Pehnelt and Vietze (2011). Nevertheless, the transesterification step should not be crucial to compare the sustainability of EU versus non-EU bio-fuels, as almost always the transesterification of bio-oil to biodiesel takes place in the EU (IFEU 2007, Pehnelt and Vietze 2011).

3.6 Reference Value

As discussed in Pehnelt and Vietze (2011), the reference value for the GHG emission savings, the average CO_2 emission resulting from the combust of fossil diesel, is problematic. Besides the direct CO_2 emission from direct combustion (73.1 kg gCO_2eq/MJ), the emissions from the extraction of fossil fuels have to be taken into account and these emissions vary depending on the very process. The EU (2009) sets the reference value for GHG emissions from fossil fuel at 83.8 g CO_2eq/MJ.

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[7]   Weindorf (2008) does not present precise input / output data.

**Table 1: GHG emissions 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 CO2eq/MJ diesel	14.2	14.2	10.2

Table 1 summarizes 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 CO2eq/MJ. The EU reference value for GHG emissions is close to the lower bound of this range and therefore rather underestimates the carbon savings of biofuels (Pehnelt and Vietze 2009, 2011). Thus, according to Pehnelt and Vietze (2011), we use two different reference values for biodiesel in our models: the EU-reference value of 83.8 g CO2eq/MJ and the value of Silva et al. (2006) and CONCAWE et al. (2006) of 87.3 g CO2eq/MJ. Additionally, in all scenarios we refer to a third reference value for rape oil used for electricity production. We use the value of 91 g CO2eq/MJ for electricity production from fossil oil regarding the 'Guidance on Sustainable Biomass Production' (Biokraft-NachV) published by the German Federal Agency for Food and Agriculture (BLE 2009) and the EU-Directive 2009/28/EC (EU 2009). As the generation of electricity operates with refined plant oil (without transesterification), we calculate the CO2 emission savings of electricity production after the refinery stage.

3.7 Allocation of By-Products

Biofuel production is a multi-input/multi-output product system. Thus, to evaluate the impacts of biofuels correctly, by-products during the production process 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 according to a comprehensible allocation factor. Among others, mass allocation, economic allocation, energy or exergy allocation, or substation method are the most used methodologies of integrating the allocation of by-products into LCA. The particular method applied is not insignificant, as it may have considerable impacts on the final results. Hence, the allocation method is also an area of extensive debate and discrepancy among different LCA studies (Menichette and Otto 2009).[8]

According to Pehnelt and Vietze (2011), a mass-based allocation scheme method that take the energy content into account, or an economic allocation scheme could be used to assess the effects of by-products. The latter takes the actual economic value of the by-products into account and – therefore – provides an (potential) income perspective by selling these co-products. As this method reflects the actual market conditions more properly than other methods such an assessment seems to be preferable for LCA.

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[8]   See for instance Weidema (2001).

However, because prices may fluctuate quite rapidly, economic allocation methods significantly increase the volatility of results and – therefore – their uncertainty.[9] Ideally, this approach has to reconduct several times to adjust a LCA study accordingly. However, this is very difficult for regulatory implementation purposes (Menichette and Otto 2009). Thus, most LCA studies on biofuels focus on other allocation methods instead. The most common allocation method is the energy allocation which takes the energy content of the by-products into account. As the calorific value of certain by-products can be measured relatively easily and without high volatilities, this is indeed a pragmatic approach.

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 (Pehnelt and Vietze 2011).[10]

Because we want to be as close as possible to the current methods of calculating GHG emissions saving potentials used for regulatory purposes, e.g. the methods applied by the EU (2009), we also use – according to IFEU (2011) and BioGrace (2010) – an allocation scheme based on the energy content of the by-products.[11]

4.   Results

We use the aforementioned input/output inventory values to run estimations on the GHG emission saving potential of rapeseed biodiesel in different scenarios. In order to provide the highest possible transparency we calculate and publish the GHG emissions of every step of the rapeseed biodiesel production chain. For all of our scenarios, we calculate the GHG emission saving potentials of refined rapeseed oil as an input in power plants (electricity production) as well as the GHG emissions saving potentials of rapeseed oil based biodiesel (FAME) according to RED and by using common esterification technologies. Thus, we present three GHG emission saving values regarding the respective fossil fuel comparator. First, we calculate values for the GHG emission savings of rape oil used for electricity production. Second, we calculate values for the GHG emissions saving potential compared to the value of fossil diesel as stated by the EU-Directive (EU 2009). And third, we calculate values for the GHG saving potential of rape biodiesel to current LCA of fossil fuel emissions, as applied by Silva et al. (2006) and CONCAWE et al. (2006). All relevant data and results are documented in detail.

The total GHG emissions of the production of refined rape oil for electricity production are ranging from about 45 g CO2eq per MJ RefRSO (scenario 1, 2, and 3) to about 50 g CO2eq per MJ RefRSO (scenario 4, 5, and 6) (see Figure 1).

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[9] In case of glycerine it is projected that by the year 2020, production will be six times higher than the demand for direct use (food, chemistry), resulting in decreasing prices. Research is being conducted to use this glycerine as upstream product for further chemical production processes (Nilles 2005; Christoph et al. 2006).

[10] Using economic allocation methods, the results are more in favour of palm oil biodiesel than for rape oil, as palm oil production generates high value by-products like palm kernel oil which is not the case for rape oil production.

[11] Moreover, this enables a direct comparison of the GHG emission saving potential of rape oil with palm oil (see Pehnelt and Vietze 2011).

Figure 1: GHG Emissions of refined Rapeseed Oil Production per Stage

GHG Emissions of Rapeseed Oil Production per Stage (g CO2 eq/MJ RefRSO)

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
transport (to port)	2.07	2.07	2.07	2.07	2.07	2.07
refinery	0.78	0.78	0.78	0.78	0.78	0.78
oil mill	5.24	5.24	5.24	5.35	5.35	5.35
plantation	36.82	36.82	36.82	40.94	40.94	40.94
total RefRSO	44.91	44.91	44.91	49.14	49.14	49.14
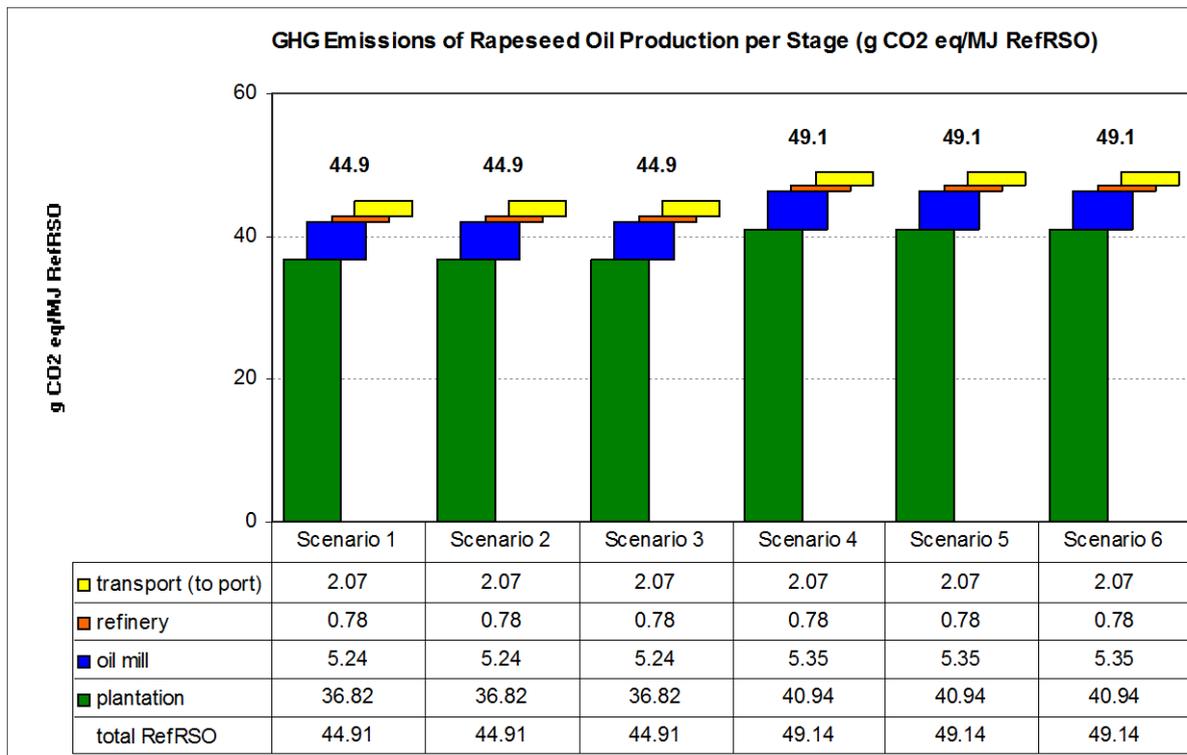
In scenario 1, 2, and 3 we use the average values (except esterification) that can be found in studies on rape oil (see Table 2 for details).

Table 2: Scenario 1, average values, esterification IFEU (2011)

Plantation	value	unit	source
output			
yield rape seed (RS) (dried, cleaned)	2697.9	kg RS / ha / year	EU-average 1991-2005: FAOSTAT 2012; drying losses (3%): Jensen et al. 2005.
input			
seed - rape seed (normed)	9	kg seeds / ha / year	Schmidt 2007, Dansk Landbrugsrådgivning 2005a, Nemecek et al. 2003
N-fertiliser	140	kg N / ha / year	Schmidt 2007, Plantedirektoratet 2005a; plantation scheme: Jacobsen et al. 2002
P2O5-fertiliser	57	kg P2O5 / ha / year	Schmidt 2007, Dansk Landbrugsrådgivning 2005a, 2005b
K2O-fertiliser	99	kg K2O / ha / year	Schmidt 2007, Dansk Landbrugsrådgivning 2005a, 2005b
CaO-fertiliser	0	kg CaO / ha / year	
Pesticides	0.27	kg ai / ha / year	Dalgaard 2007, Dalgaard et al. 2008
Diesel (all activities and transport)	112.1	l / ha / year	Schmidt 2007, values average of Nemecek et al. 2003, Dalgaard et al. 2001, 2006; no. field work processes: Nemecek et al. 2003, Dalgaard et al. 2001, 2006, Dansk Landbrugsrådgivning 2005a, Jensen et al. 2005
electricity (storage, drying of RS)	60.83	kWh / t RS	Schmidt 2007, Dalgaard et al. 2001, Nemecek et al. 2003
GHG emissions after plantation	**861.42**	**g CO2eq per kg RS**	Note: 167 Kg N/ha N-fertilizer is applied, but 27 kg N/ha can be saved for the crop after rapeseed. Therefore, the 27 kg N/ha is credited to rapeseed. The value of input-seed is normed to convential rapeseed. Diesel consumption including miscellaneaus transport, e.g. inspection of field, with 6.1 l diesel/ha (Dalgaard 2007).
GHG emissions of plantation	**1325.48**	**g CO2eq per kg RefRSO**	
GHG emissions of plantation	**36.82**	**g CO2eq per MJ RefRSO**	

t.b.c.

Table 2 continued

Refinery	value	unit	source
output			
produced RSO	983.3	t RefRSO / 1000 t RSO / year	Schmidt 2007, Hansen 2006
input			
processed RSO	1000	t RSO / year	reference value
Fuller´s earth	8.9	t / 1000 t RSO / year	Schmidt 2007, Hansen 2006
Energy consumption			
Natural gas	0	kWh / 1000 t RSO / year	Schmidt 2007, Hansen 2006; energy consumption of boiler considered as fuel oil
Fuel oil	7100	l / 1000 t RSO / year	Schmidt 2007, Hansen 2006; energy efficiency of boiler: Energistyrelsen 1995, Aarhus United 2004, 2005b; energy content of fuel oil: JEC 2011
Electricity (external)	24880	kWh / 1000 t RSO / year	Schmidt 2007, Hansen 2006; excess electricity of boiler: Energistyrelsen 1995, Aarhus United 2004, 2005b
Electricity mix	EU		Schmidt 2007, Aarhus United 2004, 2005b
GHG emission after Refinery	**1542.14**	**g CO2eq per kg RefRSO**	Note: Different to IFEU (2011) fuel oil (not natural gas) is used to produce steam in the power central. There is excess electricity from cogeneration which is considered (substracted) as non-used external electricity from grid.
GHG emissions of Refinery	**28.18**	**g CO2eq per kg RefRSO**	
GHG emissions of Refinery	**0.78**	**g CO2eq per MJ RefRSO**	

Transport (to Rotterdam)	value	unit	source
Transport (overland)			
average distance mill/refinery/port	830	km	Falk 2012
vehicle used transporting RefPO	Truck for Diesel		Schmidt 2007
used fuel for vehicle	Diesel		Schmidt 2007
GHG emissions after Transport	**1616.71**	**g CO2eq per kg RefRSO**	
GHG emissions of Transport	**74.57**	**g CO2eq per kg RefRSO**	
GHG emissions of Transport	**2.07**	**g CO2eq per MJ RefRSO**	

	value	unit	source
Total GHG emissions RefPO	**1616.71**	**g CO2eq per kg RefRSO**	
	44.91	**g CO2eq per MJ RefRSO**	
GHG emission savings compared to fossil comparator (electricity production)	**50.7%**	91 gCO2eq/MJ RED 2009/28/EC	

Esterification	value	unit	source
output			
produced FAME	988.25	t FAME / 1000 t RefRSO / year	IFEU 2011 (according to EU Directive 2009/28/EC (EU 2009))
Glycerine	104.36	t Glyc. / 1000 t RefRSO / year	IFEU 2011 (according to EU Directive 2009/28/EC (EU 2009))
input			
processed RefRSO	1000.00	t RefRSO / year	IFEU 2011 (according to EU Directive 2009/28/EC (EU 2009))
Methanol	151.19	t Meth. / 1000 t RefRSO / year	IFEU 2011 (according to EU Directive 2009/28/EC (EU 2009))
Phosporic acid (H3PO4)	2.35	t H3PO4 / 1000 t RefRSO / year	IFEU 2011 (according to EU Directive 2009/28/EC (EU 2009))
Hydrochloric acid (HCl)	27.67	t HCl / 1000 t RefRSO / year	IFEU 2011 (according to EU Directive 2009/28/EC (EU 2009))
Sodium carbonate (Na2CO3)	3.46	t Na2CO3 / 1000 t RefRSO / year	IFEU 2011 (according to EU Directive 2009/28/EC (EU 2009))
Sodium Hydroxide (NaOH)	9.30	t NaOH / 1000 t RefRSO / year	IFEU 2011 (according to EU Directive 2009/28/EC (EU 2009))
Energy consumption			
Natural gas	1141314	kWh / 1000 t RefRSO / year	IFEU 2011 (according to EU Directive 2009/28/EC (EU 2009))
Electricity (external)	62050	kWh / 1000 t RefRSO / year	IFEU 2011 (according to EU Directive 2009/28/EC (EU 2009))
Electricity mix	EU		IFEU 2011 (according to EU Directive 2009/28/EC (EU 2009))
Allocation factor after by-products	*0.957*		
CO2 emissions after Esterification	**2191.37**	**g CO2eq per kg FAME**	
CO2 emissions of Esterification	**626.51**	**g CO2eq per kg FAME**	
CO2 emissions of Esterification	**16.84**	**g CO2eq per MJ FAME**	

	value	unit	source
Total CO2 emissions FAME	**2191.37**	**g CO2eq per kg FAME**	
	58.91	**g CO2eq per MJ FAME**	
GHG emission savings compared to fossil comparator I (fuel diesel)	**29.7%**	83.8 g CO2eq/MJ RED 2009/28/EC	
GHG emission savings compared to fossil comparator II (fuel diesel)	**32.5%**	87.3 g CO2eq/MJ Silva et al. 2006; CONCAWE et al. 2006	

As in all scenarios, the energy content of rapeseed cake and glycerine is considered as a by-product. For esterification, the EU-default value on GHG emissions according to IFEU (2011) is applied in the scenario. The results of scenario 1 indicate that GHG emissions savings of rapeseed biodiesel are below the EU's 35% threshold. Precisely, the GHG emission saving potential of refined rape oil used for electricity production in (co-generation) power plants is with 50.1% compared to fossil electricity production above the EU-threshold (see Figure 2 for a comparison of all scenarios).

Figure 2: GHG Emissions Savings of refined Rapeseed Oil used in Oil fired Power Plants

GHG Emissions Savings Refined Rapeseed Oil vs. Reference Value
(RED 2009/28/EC; electricity production)

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
GHG emissions savings	50.7%	50.7%	50.7%	46.0%	46.0%	46.0%
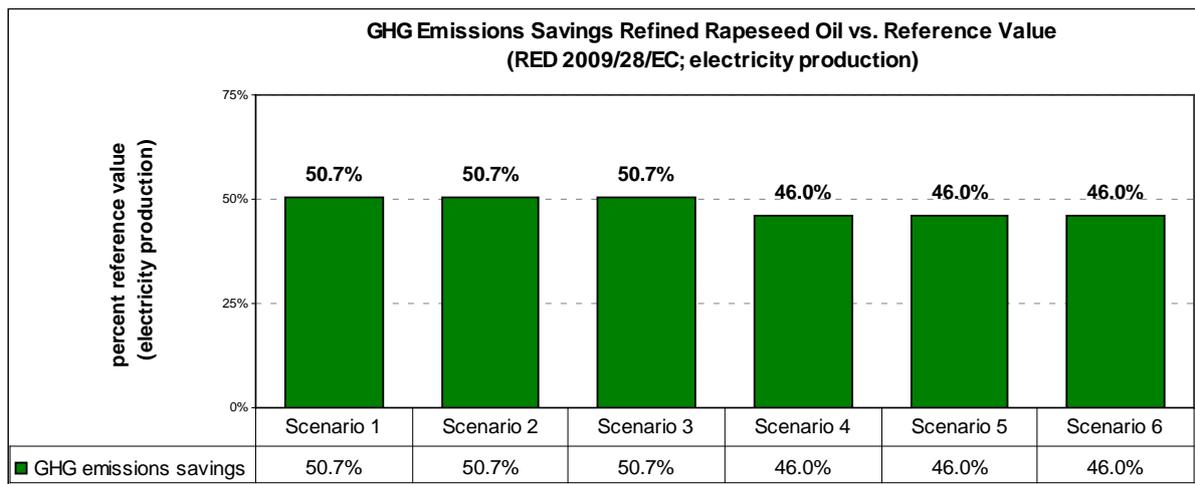
The GHG emissions of the production of rape biodiesel (FAME) ranges from 50.6 g CO2eq per MJ FAME (scenario 3) to about 62.9 g CO2eq per MJ FAME (scenario 4) (see Figure 3).

Figure 3: GHG Emissions of Rapeseed FAME Production per Stage

GHG Emissions of Rapeseed FAME Production per Stage (g CO2 eq/MJ rapeseed FAME)

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
esterification	16.84	12.65	7.10	16.84	12.65	7.10
transport (to port)	1.94	1.99	2.00	1.94	1.99	2.00
refinery	0.73	0.75	0.76	0.73	0.75	0.76
oil mill	4.90	5.03	5.07	5.01	5.13	5.18
plantation	34.49	35.35	35.63	38.35	39.31	39.62
total FAME	58.91	55.77	50.56	62.87	59.83	54.65
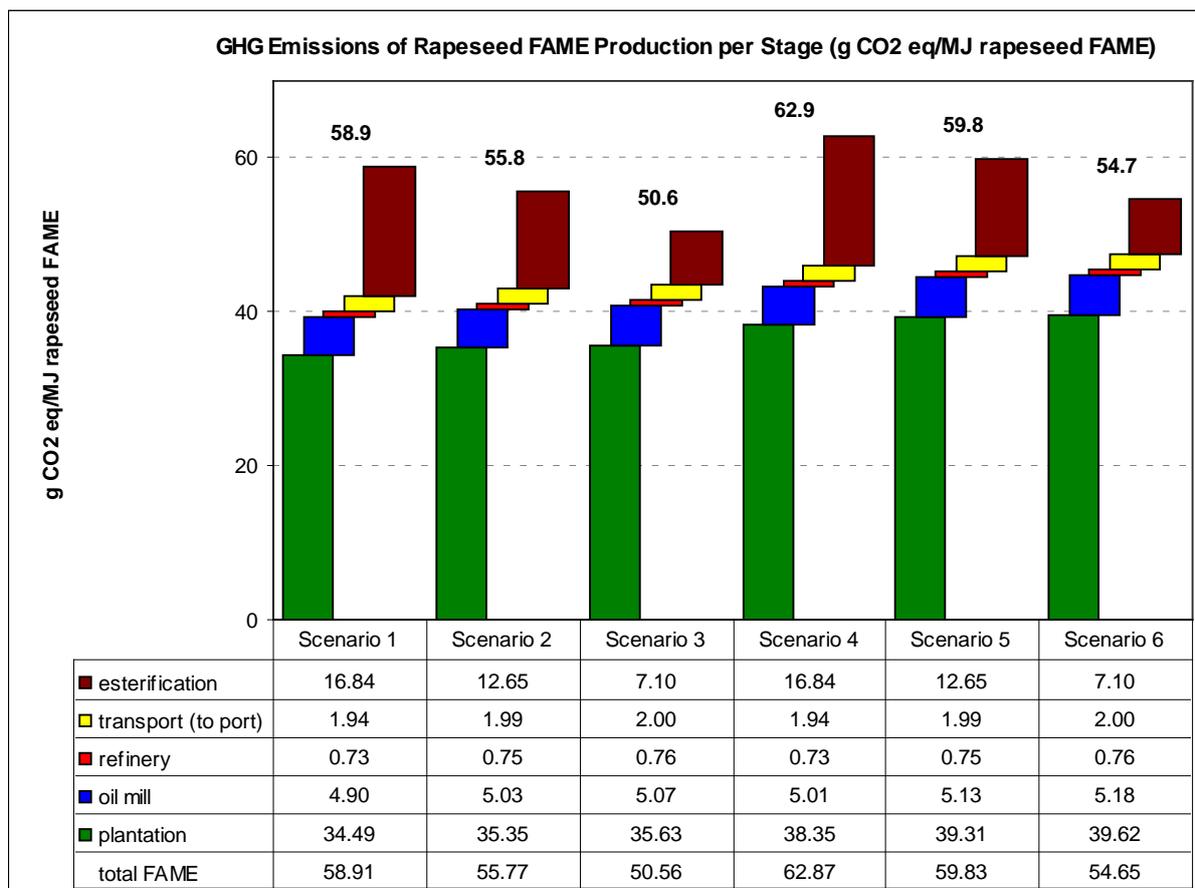
These results imply very mixed evaluation of rapeseed biodiesel ranging from a clear fulfillment of the EU requirements (35% threshold) to rather poor GHG emissions saving of rapeseed diesel compared to fossil fuel and a respective failure of the 35% threshold. Adding the emissions of esterification (according to IFEU 2011), the GHG emissions saving potential of rape diesel used in vehicle engines compared to fossil fuel ranges between 29.7% and 32.5% – dependent on the fossil comparator used – which is not meeting the EU requirements (scenario 1, see Table 2).

Using more current production values for the transesterification stage (WTT Appendix 1 (v3) according to Pehnelt and Vietze 2011) and Weindorf (2008) respectively, the GHG emission savings of rapeseed diesel turn more in favor: While in Scenario 2 (WTT, Table 4 in Annex) the GHG emission savings of rape diesel account for 33.4 % and 36.1 % respectively, emission savings of 39.7 % and 42.1 % can be reached in scenario 3 (Weindorf 2008, see Table 5 in Annex). In the latter three cases rapeseed diesel reaches the EU 35 % threshold significantly.

In scenario 4, 5, and 6 we rely on data for plantation on acid soils. In these cases lime (CaO) application is needed to reduce the soil acidity (Thamsiriroj and Murphy 2010). Additionally, we estimate the GHG emission values of rape oil taking the additive CO2eq emissions from n-hexane in the milling process into account. As further described in the methodology section, the CO2 produced from oxidation of NMVOCs (direct GWP) is not included in the emission estimates, since this carbon is included in the inventory data of produced hexane. Only the additional indirect GWP of n-hexane effluent is applied here. The emissions value (3.4-fold of CO2) of n-hexane has some significant inherent uncertainties, but clearly count for above one CO2eq (as for CO2) (Collins et al. 2002 and IPCC 2007).

Taking the emissions regarding lime production (and GHG field emissions) and the additional greenhouse warming potential of hexane into account (other data constant), the GHG emission saving potential of rapeseed biodiesel (scenario 4, esterification according to IFEU (2011), Table 6 in Annex) decreases substantially to approximately 25% (EU reference value) or 28% respectively (reference value according to Silva et al. (2006) and CONCAWE et al. (2006)).[12]

Applying the WTT inventory data for esterification (scenario 5, Table 7 in Annex) the GHG emission savings of rape diesel reaches an estimate of 28.6 % compared to the EU-reference value and 31.5 % compared to Silva et al. (2006) / CONCAWE et al. (2006) reference value. More favorable results can be estimated with regard to esterification values by Weindorf (2008) (scenario 6, Table 8), namely 34.8 % (EU 2009) and 37.4 % (Silva et al. 2006 / CONCAWE et al. 2006). Both values are close to the EU-threshold but below the RED typical as well as the default value for rapeseed oil. Again, when considering the GHG emissions relating to lime application and hexane effluent during rape oil milling process, the production and use of rapeseed biodiesel produces results worse than the RED typical or default values used by the EU.

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[12] The GHG emission savings in case of electricity production in power plants account with 46 %.

The following charts provide an overview on the GHG emissions saving potential of rapeseed FAME with respect to the two different fossil comparators. In order to show the striking differences to the values that can be found in RED, we also show the EU's 'typical' and 'default' value for rapeseed biodiesel.[13]

Figure 4: GHG Emissions Savings of Rapeseed FAME (fossil comparator I)

	RED typical	RED default	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
GHG emissions savings	45.0%	38.0%	29.7%	33.4%	39.7%	25.0%	28.6%	34.8%
RED threshold	35%	35%	35%	35%	35%	35%	35%	35%
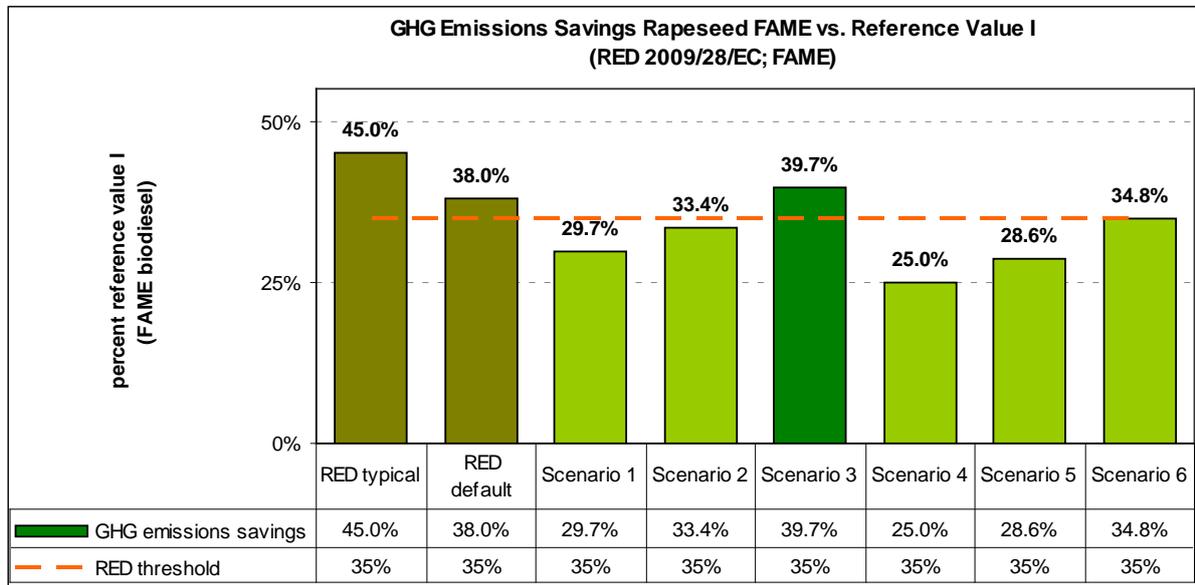
Figure 5: GHG Emissions Savings of Rapeseed FAME (fossil comparator II)

	RED typical	RED default	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
GHG emissions savings	45.0%	38.0%	32.5%	36.1%	42.1%	28.0%	31.5%	37.4%
RED threshold	35%	35%	35%	35%	35%	35%	35%	35%

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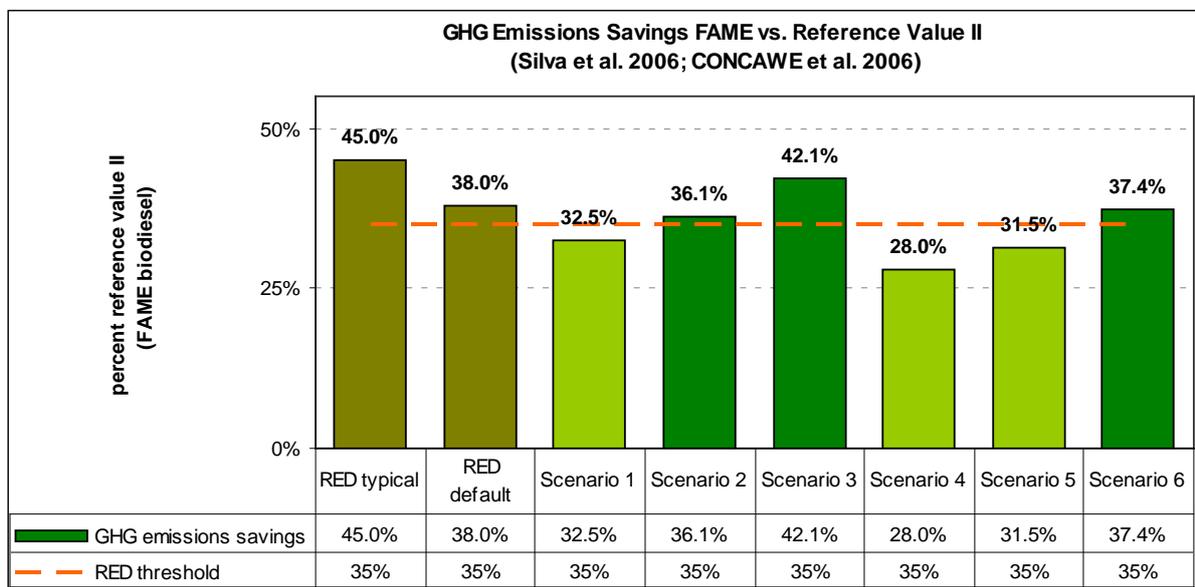
[13] Note that in both figures, the EU's 'typical' and 'default' values as they appear in the annex of RED are shown regardless the very fossil comparator. Adjusting the 'typical' and 'default' value to the fossil comparator II would result in even higher GHG emissions saving values.

To summarize these results, calculating the GHG emission savings values of rapeseed based on common conditions, production patterns and supply chains provides a quite striking range of results. If one assumes rather favorable conditions (scenario 3), rapeseed biodiesel can be referred as 'sustainable' in the EU's definition and therefore be eligible for mandatory blending. However, if rather average and less favourable production patterns are applied (e.g. scenario 1, 4 and 5), rapeseed biodiesel fails to reach the 35% threshold and would not be interpreted as 'sustainable' under the requirements of RED.

Our calculations can only justify the RED default value for rapeseed in one scenario (scenario 3). This is the only scenario where the 35% threshold is reached for both fossil comparators. Furthermore, in none of our scenarios we can verify the RED typical value for rapeseed oil production within the EU.

5. Conclusion

The aim of our paper was to analyze the GHG emission saving values of rapeseed biodiesel (FAME) as stated by RED (EU 2009). For this purpose, we run a life cycle assessment (LCA) of rapeseed biodiesel using the same basic methodology and background data as RED. Unlike other studies, we utilize only publicly available and published data in our calculations. We follow the same rather conservative approach as in a previous study on palm oil (Pehnelt and Vietze 2011) in using average values and assuming common conditions along the production chain in most of our scenarios. However, in order to enable a broad comparison, we run also calculations with more superior assumptions regarding rapeseed diesel production (e.g. esterification) compared to the average values and pathways. Moreover, in all scenarios we compare the very GHG emissions with fossil fuel emissions according RED (EU 2009) as well as with higher fossil fuel emissions according Silva et al. (2006) and CONCAWE et al. (2006). The latter is more favorable regarding GHG emission savings of rapeseed diesel.

Nevertheless, in most cases we are unable to reach the GHG emissions saving values that can be found in the annex of RED. Neither the RED typical value for rapeseed oil (45%) nor even the less stringent default value (38%) can be approved by our analysis. Furthermore, the overwhelming majority of calculations indicate that rapeseed biodiesel does not reach the 35% threshold required by the EU Directive.

By using the RED value for fossil fuel comparison only in scenario 3 (best case scenario regarding soil quality, hexane capturing in oil mill and esterification efficiency) the RED default value could be in theory roughly reproduced. The 35% threshold is only reached in this scenario. Using the fossil fuel comparator according Silva et al. (2006) and CONCAWE et al. (2006) the 35% target could conceivably be achieved marginally in scenario 2 and 6; however this would involve assuming advanced esterification technologies with rather low GHG emissions.

As far as we can assess, the assumptions and underlying data of scenario 1 come closest to the pathways used by the EU to calculate their stated values. In this scenario we are using – as in all scenarios – the same methodology as stated by the EU (2009) directive. Additionally, we obtain the same value for esterification as IFEU (2011) (according to EU Directive 2009/28/EC (EU 2009)). For the other production steps (plantation, milling, refinery and transport), we rely on the average of published input/output data, as not all of the values

assumed by RED are publicly available; nor could they be reproduced. Taking the RED reference value for fossil fuels, we calculate a GHG emissions saving value of 29.7% which is not only well below the GHG emissions saving values (default and typical) that can be found in RED but also far below the 35% threshold.

Considering two common production scenarios, namely lime (CaO) application to reduce the soil acidity in the plantation stage (Thamsiriroj and Murphy 2010) and hexane emissions during milling process (Schmidt 2007) and keeping the other values constant, we receive even lower emission saving values. In scenario 4 rapeseed biodiesel only reaches a GHG emissions saving value of 25% (fossil fuel comparator according to RED).

It is remarkable that the 'typical' value of 45% published in the annex of RED and which is usually consulted when it comes to the evaluation of whether or not biodiesel is 'sustainable' cannot be achieved by European rapeseed, in any of our scenarios.

Meanwhile, this analysis does not take into account the number of 'indirect' factors that might be considered under future application of RED with new sustainability criteria. For instance, the consideration of Indirect Land Use Change (ILUC) may have a strongly adverse impact on rapeseed biodiesel. And any consideration of the substitutability of vegetable oils, wherein vegetable oils as a whole are assessed on equal terms, will adversely affect the use of rapeseed in contrast to alternative vegetable oils. To date, assessments have failed to properly consider the interchangeable nature of vegetable oils in both food and fuel applications – neglecting the displacement of uncompetitive vegetable oils in respective markets.

To summaries, we are not able to recalculate the RED default value, not to mention the even more favorable typical values. The simple and unavoidable conclusion is that these values stated by the EU (2009) are more than questionable. Given these striking differences as well as the lack of transparency regarding the data used to calculate the 'default' and 'typical' values, one is minded to suppose that 'politically' achieved and agreed typical and default values regarding rapeseed biodiesel are preferred over scientifically proven ones.

ANNEX

Table 3: Background data

BACKGROUND DATA	parameter:	unit:	GHG emission coefficient								Fossil energy input		LHV MJ/kg (at 0% water)	Fuel efficiency	Transport exhaust gas emissions		Source
			gCO$_2$/kg	gCH$_4$/kg	gN$_2$O/kg	gCO$_{2\text{-eq}}$/kg	gCO$_2$/MJ	gCH$_4$/MJ	gN$_2$O/MJ	gCO$_{2\text{-eq}}$/MJ	MJ$_{fossil}$/kg	MJ$_{fossil}$/MJ	MJ/kg	MJ/t.km	gCH$_4$/t.km	gN$_2$O/t.km	
Global Warming Potentials (GWP's)																	
CO$_2$	1																RED Annex V.C.5
CH$_4$	25																RED Annex V.C.5
N$_2$O	298																RED Annex V.C.5
Agro inputs																	
N-fertiliser (kg N)			2827.0	8.68	9.6418	27257.4					48.99						JEC E3-database (version 31-7-2008)
P$_2$O$_5$-fertiliser (kg P$_2$O$_5$)			964.9	1.33	0.0515	145.6					15.23						JEC E3-database (version 31-7-2008)
K$_2$O-fertiliser (kg K$_2$O)			536.3	1.57	0.0123	34.8					9.68						JEC E3-database (version 31-7-2008)
CaO-fertiliser (kg CaO)			119.1	0.22	0.0183	51.7					1.97						JEC E3-database (version 31-7-2008)
Pesticides			9886.5	25.53	1.6814	4753.3					268.40						JEC E3-database (version 31-7-2008)
Seeds- rapeseed			412.1	0.91	1.0028	2834.9					7.87						JEC E3-database (version 31-7-2008)
Fuels- gasses																	
Natural gas (4000 km, Russian NG quality)							61.58	0.1981	0.0002	0.63		1.1281					JEC E3-database (version 31-7-2008)
Natural gas (4000 km, EU Mix qualilty)							62.96	0.1981	0.0002	0.63		1.1281					JEC E3-database (version 31-7-2008)
Methane													50.0				JEC E3-database (version 31-7-2008)
Fuels- liquids (also conversion inputs)																	
Diesel							87.64	-	-	0.00		1.16	43.1				JEC E3-database (version 31-7-2008)
Gasoline													43.2				JEC E3-database (version 31-7-2008)
HFO							84.98	-	-	0.00		1.088	40.5				JEC E3-database (version 31-7-2008)
HFO for maritime transport							87.20	-	-	0.00		1.088	40.5				JEC E3-database (version 31-7-2008)
Ethanol													26.81				JEC E3-database (version 31-7-2008)
Methanol							92.80	0.2900	0.0003	0.94		1.6594	19.9				JEC E3-database (version 31-7-2008)
FAME													37.2				JEC E3-database (version 31-7-2008)
Syn diesel (BtL)													44.0				JEC E3-database (version 31-7-2008)
HVO													44.0				JEC E3-database (version 31-7-2008)
PVO													36.0				JEC E3-database (version 31-7-2008)
Fuels / feedstock / byproducts - solids																	
Rapeseed													26.4				JEC E3-database (version 31-7-2008)
Waste vegetable / animal oil													37.1				JEC E3-database (version 31-7-2008)
BioOil (byproduct FAME from waste oil)													21.8				JEC E3-database (version 31-7-2008)
Crude vegetable oil													36.0				JEC E3-database (version 31-7-2008)
DDGS (10 wt% moisture)													16.0				JEC E3-database (version 31-7-2008)
Glycerol													16.0				JEC E3-database (version 31-7-2008)
Rapeseed meal													18.7				JEC E3-database (version 31-7-2008)

t.b.c.

Table 3 continued

BACKGROUND DATA parameter: unit:	GHG emission coefficient								Fossil energy input		LHV MJ/kg (at 0% water)	Fuel efficiency MJ/t.km	Transport exhaust gas emissions		Source
	gCO$_2$/kg	gCH$_4$/kg	gN$_2$O/kg	gCO$_{2\text{-eq}}$/kg	gCO$_2$/MJ	gCH$_4$/MJ	gN$_2$O/MJ	gCO$_{2\text{-eq}}$/MJ	MJ$_{fossil}$/kg	MJ$_{fossil}$/MJ			gCH$_4$/t.km	gN$_2$O/t.km	
Electricity															
Electricity EU mix MV					119.36	0.2911	0.0054	15.23		2.6951					JEC E3-database (version 31-7-2008)
Electricity EU mix LV					120.79	0.2946	0.0055	15.47		2.7275					JEC E3-database (version 31-7-2008)
Conversion inputs															
n-Hexane					80.08	0.0146	0.0003	0.79		0.3204	45.1				JEC E3-database (version 31-7-2008)
Phosphoric acid (H$_3$PO$_4$)	2776.0	8.93	0.1028	290.6					28.57						JEC E3-database (version 31-7-2008)
Fuller's earth	197.0	0.04	0.0063	17.8					2.54						JEC E3-database (version 31-7-2008)
Hydrochloric acid (HCl)	717.4	1.13	0.0254	71.8					15.43						JEC E3-database (version 31-7-2008)
Sodium carbonate (Na$_2$CO$_3$)	1046.0	6.20	0.0055	15.5					13.79						JEC E3-database (version 31-7-2008)
Sodium hydroxide (NaOH)	438.5	1.03	0.0240	67.8					10.22						JEC E3-database (version 31-7-2008)
Potassium hydroxide (KOH)	0.0	0.00	0.0000	0.0					0.00						
Hydrogen (for HVO)					80.87	0.2765	0.0003	0.86		1.4835					JEC E3-database (version 31-7-2008)
Pure CaO for processes	1013.0	0.65	0.0076	21.5					4.60						JEC E3-database (version 31-7-2008)
Sulphuric acid (H$_2$SO$_4$)	193.9	0.55	0.0045	12.7					3.90						JEC E3-database (version 31-7-2008)
Ammonia	2478.0	7.84	0.0087	24.6					44.39						JEC E3-database (version 31-7-2008)
Cycle-hexane	723.0	0.00	0.0000	0.0					53.10						JEC E3-database (version 31-7-2008)
Lubricants	947.0	0.00	0.0000	0.0					53.28						JEC E3-database (version 31-7-2008)
Transport efficiencies															
Truck for dry product (Diesel)												0.94	0.005	0.0000	JEC E3-database (version 31-7-2008)
Truck for liquids (Diesel)												1.01	0.005	0.0000	
Ocean bulk carrier (Fuel oil)												0.20	0.000	0.0007	JEC E3-database (version 31-7-2008)
Ship /product tanker 50kt (Fuel oil)												0.12	0.000	0.0000	JEC E3-database (version 31-7-2008)
Local (10 km) pipeline												0.00	0.000	0.0000	JEC E3-database (version 31-7-2008)
Emissions from steam production (per MJ steam or heat)															
CH$_4$ and N$_2$O emissions from NG boiler						0.0028	0.0011	3.14							JEC E3-database (version 31-7-2008)
CH$_4$ and N$_2$O emissions from NG CHP						0.0000	0.0000	0.00							JEC E3-database (version 31-7-2008)
CH$_4$ and N$_2$O emissions from Lignite CHP						0.0023	0.0126	35.65							JEC E3-database (version 31-7-2008)
CH$_4$ and N$_2$O emissions from NG gas engine						0.0533	0.0000	0.00							JEC E3-database (version 31-7-2008)

Source: Own compilation according IFEU (2011)

Table 4: Scenario 2 – Average values, esterification WTT Appendix 1 (v3)

Plantation	value	unit	source
output			
yield rape seed (RS) (dried, cleaned)	2697.9	kg RS / ha / year	EU-average 1991-2005: FAOSTAT 2012; drying losses (3%): Jensen et al. 2005.
input			
seed - rape seed (normed)	9	kg seeds / ha / year	Schmidt 2007, Dansk Landbrugsrådgivning 2005a, Nemecek et al. 2003
N-fertiliser	140	kg N / ha / year	Schmidt 2007, Plantedirektoratet 2005a; plantation scheme: Jacobsen et al. 2002
P2O5-fertiliser	57	kg P2O5 / ha / year	Schmidt 2007, Dansk Landbrugsrådgivning 2005a, 2005b
K2O-fertiliser	99	kg K2O / ha / year	Schmidt 2007, Dansk Landbrugsrådgivning 2005a, 2005b
CaO-fertiliser	0	kg CaO / ha / year	
Pesticides	0.27	kg ai / ha / year	Dalgaard 2007, Dalgaard et al. 2008
Diesel (all activities and transport)	112.1	l / ha / year	Schmidt 2007, values average of Nemecek et al. 2003, Dalgaard et al. 2001, 2006; no. field work processes: Nemecek et al. 2003, Dalgaard et al. 2001, 2006, Dansk Landbrugsrådgivning 2005a, Jensen et al. 2005
electricity (storage, drying of RS)	60.83	kWh / t RS	Schmidt 2007, Dalgaard et al. 2001, Nemecek et al. 2003
GHG emissions after plantation	**861.42**	**g CO2eq per kg RS**	Note: 167 Kg N/ha N-fertilizer is applied, but 27 kg N/ha can be saved for the crop after rapeseed. Therefore, the 27 kg N/ha is credited to rapeseed. The value of input-seed is normed to convential rapeseed. Diesel consumption including miscellaneaus transport, e.g. inspection of field, with 6.1 l diesel/ha (Dalgaard 2007).
GHG emissions of plantation	**1325.48**	**g CO2eq per kg RefRSO**	
GHG emissions of plantation	**36.82**	**g CO2eq per MJ RefRSO**	

Oil Mill	value	unit	source
output			
produced Rape Seed Oil (RSO)	418.9	t RSO / 1000 t RS / year	Aarhus United 2005a, Schmidt 2007, efficiency: Oil World 2005
Rape Seed Cake (RSC) (by-product)	563.8	t RSC / 1000 t RS / year	Aarhus United, 2005a, Schmidt 2007, Korning 2006, Kronborg 2006, Hansen 2006
Residual oil content RSC	4	per cent of RSC	Møller et al. 2000
input / hexan-emissions			
processed Rape Seed (RS) per year	1000	t RS per year	reference value
RS losses (drying, washing, transport)	1.7	per cent of RS	Oil World 2005
n-Hexane	498	kg / 1000 t RS / year	Schmidt 2007, Kronborg 2006, Aarhus United 2005a
CO2eq emissions from n-Hexane	0.00	g CO2eq per kg RSO	
Energy consumption			
Fuel oil (light)	21210	l / 1000 t RS / year	Schmidt 2007, Kronborg 2006, Aarhus United 2005b; energy efficiency of boiler: Energistyrelsen 1995, Aarhus United 2004, 2005b; energy content fuel oil: JEC 2011
Natural gas	0	kWh / 1000 t RS / year	Schmidt 2007, Kronborg 2006, Aarhus United 2005b; energy consumption of boiler considered as fuel oil
Electricity (external)	38236	kWh / 1000 t RS / year	Schmidt 2007, Kronborg 2006, Aarhus United 2005b; excess electricity of boiler: Energistyrelsen 1995, Aarhus United 2004, 2005b
Electricity mix	EU		Schmidt 2007, Aarhus United 2004, 2005b
Transport			
average distance plantation/oil mill	100	km	Schmidt 2007
Allocation factor after by-products	0.634		
GHG emissions after Oil Mill	**1488.68**	**g CO2eq per kg RSO**	Note: Fuel oil is used to produce steam in the power central. Excess electricity from cogeneration is considered as non-used external electricity from grid.
GHG emissions of Oil Mill	**188.48**	**g CO2eq per kg RefRSO**	
GHG emissions of Oil Mill	**5.24**	**g CO2eq per MJ RefRSO**	

Refinery	value	unit	source
output			
produced RSO	983.3	t RefRSO / 1000 t RSO / year	Schmidt 2007, Hansen 2006
input			
processed RSO	1000	t RSO / year	reference value
Fuller´s earth	8.9	t / 1000 t RSO / year	Schmidt 2007, Hansen 2006
Energy consumption			
Natural gas	0	kWh / 1000 t RSO / year	Schmidt 2007, Hansen 2006; energy consumption of boiler considered as fuel oil
Fuel oil	7100	l / 1000 t RSO / year	Schmidt 2007, Hansen 2006; energy efficiency of boiler: Energistyrelsen 1995, Aarhus United 2004, 2005b; energy content of fuel oil: JEC 2011
Electricity (external)	24880	kWh / 1000 t RSO / year	Schmidt 2007, Hansen 2006; excess electricity of boiler: Energistyrelsen 1995, Aarhus United 2004, 2005b
Electricity mix	EU		Schmidt 2007, Aarhus United 2004, 2005b
GHG emission after Refinery	**1542.14**	**g CO2eq per kg RefRSO**	Note: Different to IFEU (2011) fuel oil (not natural gas) is used to produce steam in the power central. There is excess electricity from cogeneration which is considered (substracted) as non-used external electricity from grid.
GHG emissions of Refinery	**28.18**	**g CO2eq per kg RefRSO**	
GHG emissions of Refinery	**0.78**	**g CO2eq per MJ RefRSO**	

Transport (to Rotterdam)	value	unit	source
Transport (overland)			
average distance mill/refinery/port	830	km	Falk 2012
vehicle used transporting RefPO	Truck for Diesel		Schmidt 2007
used fuel for vehicle	Diesel		Schmidt 2007
GHG emissions after Transport	**1616.71**	**g CO2eq per kg RefRSO**	
GHG emissions of Transport	**74.57**	**g CO2eq per kg RefRSO**	
GHG emissions of Transport	**2.07**	**g CO2eq per MJ RefRSO**	

Total GHG emissions RefPO	**1616.71**	**g CO2eq per kg RefRSO**	
	44.91	**g CO2eq per MJ RefRSO**	
GHG emission savings compared to fossil comparator (electricity production)	**50.7%**	91 gCO2eq/MJ RED 2009/28/EC	

t.b.c.

Table 4 continued

Esterification	value	unit	source
output			
produced FAME	964.35	t FAME / 1000 t RefRSO / year	Pehnelt and Vietze 2011 (according to WTT Appendix 1 (v3))
Glycerine	101.26	t Glyc. / 1000 t RefRSO / year	Pehnelt and Vietze 2011 (according to WTT Appendix 1 (v3))
input			
processed RefRSO	1000.00	t RefRSO / year	Pehnelt and Vietze 2011 (according to WTT Appendix 1 (v3))
Methanol	106.36	t Meth. / 1000 t RefRSO / year	Pehnelt and Vietze 2011 (according to WTT Appendix 1 (v3))
Phosporic acid (H3PO4)	1.79	t H3PO4 / 1000 t RefRSO / year	Pehnelt and Vietze 2011 (according to WTT Appendix 1 (v3))
Hydrochloric acid (HCl)	19.73	t HCl / 1000 t RefRSO / year	Pehnelt and Vietze 2011 (according to WTT Appendix 1 (v3))
Sodium carbonate (Na2CO3)	2.44	t Na2CO3 / 1000 t RefRSO / year	Pehnelt and Vietze 2011 (according to WTT Appendix 1 (v3))
Sodium Hydroxide (NaOH)	6.64	t NaOH / 1000 t RefRSO / year	Pehnelt and Vietze 2011 (according to WTT Appendix 1 (v3))
Energy consumption			
Natural gas	825102	kWh / 1000 t RefRSO / year	Pehnelt and Vietze 2011 (according to WTT Appendix 1 (v3))
Electricity (external)	71748	kWh / 1000 t RefRSO / year	Pehnelt and Vietze 2011 (according to WTT Appendix 1 (v3))
Electricity mix	EU		Pehnelt and Vietze 2011 (according to WTT Appendix 1 (v3))
Allocation factor after by-products	0.957		

CO2 emissions after Esterification	2074.76	g CO2eq per kg FAME
CO2 emissions of Esterification	470.74	g CO2eq per kg FAME
CO2 emissions of Esterification	12.65	g CO2eq per MJ FAME

Total CO2 emissions FAME	2074.76	g CO2eq per kg FAME
	55.77	g CO2eq per MJ FAME
GHG emission savings compared to fossil comparator I (fuel diesel)	33.4%	83.8 g CO2eq/MJ RED 2009/28/EC
GHG emission savings compared to fossil comparator II (fuel diesel)	36.1%	87.3 g CO2eq/MJ Silva et al. 2006; CONCAWE et al. 2006

Table 5: Scenario 3 – Average values, esterification Weindorf (2008)

Plantation	value	unit	source
output			
yield rape seed (RS) (dried, cleaned)	2697.9	kg RS / ha / year	EU-average 1991-2005: FAOSTAT 2012; drying losses (3%): Jensen et al. 2005.
input			
seed - rape seed (normed)	9	kg seeds / ha / year	Schmidt 2007, Dansk Landbrugsrådgivning 2005a, Nemecek et al. 2003
N-fertiliser	140	kg N / ha / year	Schmidt 2007, Plantedirektoratet 2005a; plantation scheme: Jacobsen et al. 2002
P2O5-fertiliser	57	kg P2O5 / ha / year	Schmidt 2007, Dansk Landbrugsrådgivning 2005a, 2005b
K2O-fertiliser	99	kg K2O / ha / year	Schmidt 2007, Dansk Landbrugsrådgivning 2005a, 2005b
CaO-fertiliser	0	kg CaO / ha / year	
Pesticides	0.27	kg ai / ha / year	Dalgaard 2007, Dalgaard et al. 2008
Diesel (all activities and transport)	112.1	l / ha / year	Schmidt 2007, values average of Nemecek et al. 2003, Dalgaard et al. 2001, 2006; no. field work processes: Nemecek et al. 2003, Dalgaard et al. 2001, 2006, Dansk Landbrugsrådgivning 2005a, Jensen et al. 2005
electricity (storage, drying of RS)	60.83	kWh / t RS	Schmidt 2007, Dalgaard et al. 2001, Nemecek et al. 2003
GHG emissions after plantation	**861.42**	**g CO2eq per kg RS**	Note: 167 Kg N/ha N-fertilizer is applied, but 27 kg N/ha can be saved for the crop after rapeseed. Therefore, the 27 kg N/ha is credited to rapeseed. The value of input-seed is normed to convential rapeseed. Diesel consumption including miscellaneaus transport, e.g. inspection of field, with 6.1 l diesel/ha (Dalgaard 2007).
GHG emissions of plantation	**1325.48**	**g CO2eq per kg RefRSO**	
GHG emissions of plantation	**36.82**	**g CO2eq per MJ RefRSO**	

Oil Mill	value	unit	source
output			
produced Rape Seed Oil (RSO)	418.9	t RSO / 1000 t RS / year	Aarhus United 2005a, Schmidt 2007, efficiency: Oil World 2005
Rape Seed Cake (RSC) (by-product)	563.8	t RSC / 1000 t RS / year	Aarhus United, 2005a, Schmidt 2007, Korning 2006, Kronborg 2006, Hansen 2006
Residual oil content RSC	4	per cent of RSC	Møller et al. 2000
input / hexan-emissions			
processed Rape Seed (RS) per year	1000	t RS per year	reference value
RS losses (drying, washing, transport)	1.7	per cent of RS	Oil World 2005
n-Hexane	498	kg / 1000 t RS / year	Schmidt 2007, Kronborg 2006, Aarhus United 2005a
CO2eq emissions from n-Hexane	0.00	g CO2eq per kg RSO	
Energy consumption			
Fuel oil (light)	21210	l / 1000 t RS / year	Schmidt 2007, Kronborg 2006, Aarhus United 2005b; energy efficiency of boiler: Energistyrelsen 1995, Aarhus United 2004b, 2005b; energy content fuel oil: JEC 2011
Natural gas	0	kWh / 1000 t RS / year	Schmidt 2007, Kronborg 2006, Aarhus United 2005b; energy consumption of boiler considered as fuel oil
Electricity (external)	38236	kWh / 1000 t RS / year	Schmidt 2007, Kronborg 2006, Aarhus United 2005b; excess electricity of boiler: Energistyrelsen 1995, Aarhus United 2004, 2005b
Electricity mix	EU		Schmidt 2007, Aarhus United 2004, 2005b
Transport			
average distance plantation/oil mill	100	km	Schmidt 2007
Allocation factor after by-products	0.634		
GHG emissions after Oil Mill	**1488.68**	**g CO2eq per kg RSO**	Note: Fuel oil is used to produce steam in the power central. Excess electricity from cogeneration is considered as non-used external electricity from grid.
GHG emissions of Oil Mill	**188.48**	**g CO2eq per kg RefRSO**	
GHG emissions of Oil Mill	**5.24**	**g CO2eq per MJ RefRSO**	

Refinery	value	unit	source
output			
produced RSO	983.3	t RefRSO / 1000 t RSO / year	Schmidt 2007, Hansen 2006
input			
processed RSO	1000	t RSO / year	reference value
Fuller´s earth	8.9	t / 1000 t RSO / year	Schmidt 2007, Hansen 2006
Energy consumption			
Natural gas	0	kWh / 1000 t RSO / year	Schmidt 2007, Hansen 2006; energy consumption of boiler considered as fuel oil
Fuel oil	7100	l / 1000 t RSO / year	Schmidt 2007, Hansen 2006; energy efficiency of boiler: Energistyrelsen 1995, Aarhus United 2004, 2005b; energy content of fuel oil: JEC 2011
Electricity (external)	24880	kWh / 1000 t RSO / year	Schmidt 2007, Hansen 2006; excess electricity of boiler: Energistyrelsen 1995, Aarhus United 2004, 2005b
Electricity mix	EU		Schmidt 2007, Aarhus United 2004, 2005b
GHG emission after Refinery	**1542.14**	**g CO2eq per kg RefRSO**	Note: Different to IFEU (2011) fuel oil (not natural gas) is used to produce steam in the power central. There is excess electricity from cogeneration which is considered (substracted) as non-used external electricity from grid.
GHG emissions of Refinery	**28.18**	**g CO2eq per kg RefRSO**	
GHG emissions of Refinery	**0.78**	**g CO2eq per MJ RefRSO**	

Transport (to Rotterdam)	value	unit	source
Transport (overland)			
average distance mill/refinery/port	830	km	Falk 2012
vehicle used transporting RefPO	Truck for Diesel		Schmidt 2007
used fuel for vehicle	Diesel		Schmidt 2007
GHG emissions after Transport	**1616.71**	**g CO2eq per kg RefRSO**	
GHG emissions of Transport	**74.57**	**g CO2eq per kg RefRSO**	
GHG emissions of Transport	**2.07**	**g CO2eq per MJ RefRSO**	

	value	unit	source
Total GHG emissions RefPO	**1616.71**	**g CO2eq per kg RefRSO**	
	44.91	**g CO2eq per MJ RefRSO**	
GHG emission savings compared to fossil comparator (electricity production)	**50.7%**	91 gCO2eq/MJ RED 2009/28/EC	

Esterification	value	unit	source
CO2 emissions after Esterification	**1880.83**	**g CO2eq per kg FAME**	Weindorf 2008
CO2 emissions of Esterification	**264.12**	**g CO2eq per kg FAME**	Weindorf 2008
CO2 emissions of Esterification	**7.10**	**g CO2eq per MJ FAME**	Weindorf 2008

	value	unit	source
Total CO2 emissions FAME	**1880.83**	**g CO2eq per kg FAME**	
	50.56	**g CO2eq per MJ FAME**	
GHG emission savings compared to fossil comparator I (fuel diesel)	**39.7%**	83.8 g CO2eq/MJ RED 2009/28/EC	
GHG emission savings compared to fossil comparator II (fuel diesel)	**42.1%**	87.3 g CO2eq/MJ Silva et al. 2006; CONCAWE et al. 2006	

Table 6: Scenario 4 – Soil acidity and hexane emissions, esterification IFEU (2011)

Plantation	value	unit	source
output			
yield rape seed (RS) (dried, cleaned)	2697.9	kg RS / ha / year	EU-average 1991-2005: FAOSTAT 2012; drying losses (3%): Jensen et al. 2005.
input			
seed - rape seed (normed)	9	kg seeds / ha / year	Schmidt 2007, Dansk Landbrugsrådgivning 2005a, Nemecek et al. 2003
N-fertiliser	140	kg N / ha / year	Schmidt 2007, Plantedirektoratet 2005a; plantation scheme: Jacobsen et al. 2002
P2O5-fertiliser	57	kg P2O5 / ha / year	Schmidt 2007, Dansk Landbrugsrådgivning 2005a, 2005b
K2O-fertiliser	99	kg K2O / ha / year	Schmidt 2007, Dansk Landbrugsrådgivning 2005a, 2005b
CaO-fertiliser	2000	kg CaO / ha / year	Thamsiriroj and Murphy 2010
Pesticides	0.27	kg ai / ha / year	Dalgaard 2007, Dalgaard et al. 2008
Diesel (all activities and transport)	112.1	l / ha / year	Schmidt 2007, values average of Nemecek et al. 2003, Dalgaard et al. 2001, 2006; no. field work processes: Nemecek et al. 2003, Dalgaard et al. 2001, 2006, Dansk Landbrugsrådgivning 2005a, Jensen et al. 2005
electricity (storage, drying of RS)	60.83	kWh / t RS	Schmidt 2007, Dalgaard et al. 2001, Nemecek et al. 2003
GHG emissions after plantation	**957.77**	**g CO2eq per kg RS**	Note: 167 Kg N/ha N-fertilizer is applied, but 27 kg N/ha can be saved for the crop after rapeseed. Therefore, the 27 kg N/ha is credited to rapeseed. The value of input-seed is normed to convential rapeseed. Diesel consumption including miscellaneaus transport, e.g. inspection of field, with 6.1 l diesel/ha (Dalgaard 2007). Lime (CaO) application to reduce the soil acidity (Thamsiriroj and Murphy 2010).
GHG emissions of plantation	**1473.73**	**g CO2eq per kg RefRSO**	
GHG emissions of plantation	**40.94**	**g CO2eq per MJ RefRSO**	

Oil Mill	value	unit	source
output			
produced Rape Seed Oil (RSO)	418.9	t RSO / 1000 t RS / year	Aarhus United 2005a, Schmidt 2007, efficiency: Oil World 2005
Rape Seed Cake (RSC) (by-product)	563.8	t RSC / 1000 t RS / year	Aarhus United, 2005a, Schmidt 2007, Korning 2006, Kronborg 2006, Hansen 2006
Residual oil content RSC	4	per cent of RSC	Møller et al. 2000
input / hexan-emissions			
processed Rape Seed (RS) per year	1000	t RS per year	reference value
RS losses (drying, washing, transport)	1.7	per cent of RS	Oil World 2005
n-Hexane	498	kg / 1000 t RS / year	Schmidt 2007, Kronborg 2006, Aarhus United 2005a
CO2eq emissions from n-Hexane	2.35	kg CO2eq per t RSO	hexane emissions: Schmidt 2007, Aarhus United 2005a; estimation of CO2eq emissions: IPCC 2007, Collins et al. 2002
Energy consumption			
Fuel oil (light)	21210	l / 1000 t RS / year	Schmidt 2007, Kronborg 2006, Aarhus United 2005b; energy efficiency of boiler: Energistyrelsen 1995, Aarhus United 2004, 2005b; energy content fuel oil: JEC 2011
Natural gas	0	kWh / 1000 t RS / year	Schmidt 2007, Kronborg 2006, Aarhus United 2005b; energy consumption of boiler considered as fuel oil
Electricity (external)	38236	kWh / 1000 t RS / year	Schmidt 2007, Kronborg 2006, Aarhus United 2005b; excess electricity of boiler: Energistyrelsen 1995, Aarhus United 2004, 2005b
Electricity mix	EU		Schmidt 2007, Aarhus United 2004, 2005b
Transport			
average distance plantation/oil mill	100	km	Schmidt 2007
Allocation factor after by-products	*0.634*		
GHG emissions after Oil Mill	**1638.42**	**g CO2eq per kg RSO**	Note: Fuel oil is used to produce steam in the power central. Excess electricity from cogeneration is considered as non-used external electricity from grid. The CO2 from oxidation of hexane (direct GWP) is not included in the emission value; this carbon is included in the inventory data of hexane. Only the additional indirect GWP of hexane effluent is applied here.
GHG emissions of Oil Mill	**192.52**	**g CO2eq per kg RefRSO**	
GHG emissions of Oil Mill	**5.35**	**g CO2eq per MJ RefRSO**	

Refinery	value	unit	source
output			
produced RSO	983.3	t RefRSO / 1000 t RSO / year	Schmidt 2007, Hansen 2006
input			
processed RSO	1000	t RSO / year	reference value
Fuller´s earth	8.9	t / 1000 t RSO / year	Schmidt 2007, Hansen 2006
Energy consumption			
Natural gas	0	kWh / 1000 t RSO / year	Schmidt 2007, Hansen 2006; energy consumption of boiler considered as fuel oil
Fuel oil	7100	l / 1000 t RSO / year	Schmidt 2007, Hansen 2006; energy efficiency of boiler: Energistyrelsen 1995, Aarhus United 2004, 2005b; energy content of fuel oil: JEC 2011
Electricity (external)	24880	kWh / 1000 t RSO / year	Schmidt 2007, Hansen 2006; excess electricity of boiler: Energistyrelsen 1995, Aarhus United 2004, 2005b
Electricity mix	EU		Schmidt 2007, Aarhus United 2004, 2005b
GHG emission after Refinery	**1694.42**	**g CO2eq per kg RefRSO**	Note: Different to IFEU (2011) fuel oil (not natural gas) is used to produce steam in the power central. There is excess electricity from cogeneration which is considered (substracted) as non-used external electricity from grid.
GHG emissions of Refinery	**28.18**	**g CO2eq per kg RefRSO**	
GHG emissions of Refinery	**0.78**	**g CO2eq per MJ RefRSO**	

Transport (to Rotterdam)	value	unit	source
Transport (overland)			
average distance mill/refinery/port	830	km	Falk 2012
vehicle used transporting RefPO	Truck for Diesel		Schmidt 2007
used fuel for vehicle	Diesel		Schmidt 2007
GHG emissions after Transport	**1768.99**	**g CO2eq per kg RefRSO**	
GHG emissions of Transport	**74.57**	**g CO2eq per kg RefRSO**	
GHG emissions of Transport	**2.07**	**g CO2eq per MJ RefRSO**	

	value	unit
Total GHG emissions RefPO	**1768.99**	**g CO2eq per kg RefRSO**
	49.14	**g CO2eq per MJ RefRSO**
GHG emission savings compared to fossil comparator (electricity production)	**46.0%**	91 gCO2eq/MJ RED 2009/28/EC

t.b.c.

Table 6 continued

Esterification	value	unit	source
output			
produced FAME	988.25	t FAME / 1000 t RefRSO / year	IFEU 2011 (according to EU Directive 2009/28/EC (EU 2009))
Glycerine	104.36	t Glyc. / 1000 t RefRSO / year	IFEU 2011 (according to EU Directive 2009/28/EC (EU 2009))
input			
processed RefRSO	1000.00	t RefRSO / year	IFEU 2011 (according to EU Directive 2009/28/EC (EU 2009))
Methanol	151.19	t Meth. / 1000 t RefRSO / year	IFEU 2011 (according to EU Directive 2009/28/EC (EU 2009))
Phosporic acid (H3PO4)	2.35	t H3PO4 / 1000 t RefRSO / year	IFEU 2011 (according to EU Directive 2009/28/EC (EU 2009))
Hydrochloric acid (HCl)	27.67	t HCl / 1000 t RefRSO / year	IFEU 2011 (according to EU Directive 2009/28/EC (EU 2009))
Sodium carbonate (Na2CO3)	3.46	t Na2CO3 / 1000 t RefRSO / year	IFEU 2011 (according to EU Directive 2009/28/EC (EU 2009))
Sodium Hydroxide (NaOH)	9.30	t NaOH / 1000 t RefRSO / year	IFEU 2011 (according to EU Directive 2009/28/EC (EU 2009))
Energy consumption			
Natural gas	1141314	kWh / 1000 t RefRSO / year	IFEU 2011 (according to EU Directive 2009/28/EC (EU 2009))
Electricity (external)	62050	kWh / 1000 t RefRSO / year	IFEU 2011 (according to EU Directive 2009/28/EC (EU 2009))
Electricity mix	EU		IFEU 2011 (according to EU Directive 2009/28/EC (EU 2009))
Allocation factor after by-products	0.957		

CO2 emissions after Esterification	2338.76	g CO2eq per kg FAME	
CO2 emissions of Esterification	626.51	g CO2eq per kg FAME	
CO2 emissions of Esterification	16.84	g CO2eq per MJ FAME	

Total CO2 emissions FAME	2338.76	g CO2eq per kg FAME	
	62.87	g CO2eq per MJ FAME	
GHG emission savings compared to fossil comparator I (fuel diesel)	25.0%	83.8 g CO2eq/MJ RED 2009/28/EC	
GHG emission savings compared to fossil comparator II (fuel diesel)	28.0%	87.3 g CO2eq/MJ Silva et al. 2006; CONCAWE et al. 2006	

Table 7: Scenario 5 – Soil acidity and hexane emissions, esterification WTT Appendix 1 (v3)

Plantation	value	unit	source
output			
yield rape seed (RS) (dried, cleaned)	2697.9	kg RS / ha / year	EU-average 1991-2005: FAOSTAT 2012; drying losses (3%): Jensen et al. 2005.
input			
seed - rape seed (normed)	9	kg seeds / ha / year	Schmidt 2007, Dansk Landbrugsrådgivning 2005a, Nemecek et al. 2003
N-fertiliser	140	kg N / ha / year	Schmidt 2007, Plantedirektoratet 2005a; plantation scheme: Jacobsen et al. 2002
P2O5-fertiliser	57	kg P2O5 / ha / year	Schmidt 2007, Dansk Landbrugsrådgivning 2005a, 2005b
K2O-fertiliser	99	kg K2O / ha / year	Schmidt 2007, Dansk Landbrugsrådgivning 2005a, 2005b
CaO-fertiliser	2000	kg CaO / ha / year	Thamsiriroj and Murphy 2010
Pesticides	0.27	kg ai / ha / year	Dalgaard 2007, Dalgaard et al. 2008
Diesel (all activities and transport)	112.1	l / ha / year	Schmidt 2007, values average of Nemecek et al. 2003, Dalgaard et al. 2001, 2006; no. field work processes: Nemecek et al. 2003, Dalgaard et al. 2001, 2006, Dansk Landbrugsrådgivning 2005a, Jensen et al. 2005
electricity (storage, drying of RS)	60.83	kWh / t RS	Schmidt 2007, Dalgaard et al. 2001, Nemecek et al. 2003

GHG emissions after plantation	957.77	g CO2eq per kg RS	Note: 167 Kg N/ha N-fertilizer is applied, but 27 kg N/ha can be saved for the crop after rapeseed. Therefore, the 27 kg N/ha is credited to rapeseed. The value of input-seed is normed to conventional rapeseed. Diesel consumption including miscellaneous transport, e.g. inspection of field, with 6.1 l diesel/ha (Dalgaard 2007). Lime (CaO) application to reduce the soil acidity (Thamsiriroj and Murphy 2010).
GHG emissions of plantation	1473.73	g CO2eq per kg RefRSO	
GHG emissions of plantation	40.94	g CO2eq per MJ RefRSO	

Oil Mill	value	unit	source
output			
produced Rape Seed Oil (RSO)	418.9	t RSO / 1000 t RS / year	Aarhus United 2005a, Schmidt 2007, efficiency: Oil World 2005
Rape Seed Cake (RSC) (by-product)	563.8	t RSC / 1000 t RS / year	Aarhus United, 2005a, Schmidt 2007, Korning 2006, Kronborg 2006, Hansen 2006
Residual oil content RSC	4	per cent of RSC	Møller et al. 2000
input / hexan-emissions			
processed Rape Seed (RS) per year	1000	t RS per year	reference value
RS losses (drying, washing, transport)	1.7	per cent of RS	Oil World 2005
n-Hexane	498	kg / 1000 t RS / year	Schmidt 2007, Kronborg 2006, Aarhus United 2005a
CO2eq emissions from n-Hexane	2.35	kg CO2eq per t RSO	hexane emissions: Schmidt 2007, Aarhus United 2005a; estimation of CO2eq emissions: IPCC 2007, Collins et al. 2002
Energy consumption			
Fuel oil (light)	21210	l / 1000 t RS / year	Schmidt 2007, Kronborg 2006, Aarhus United 2005b; energy efficiency of boiler: Energistyrelsen 1995, Aarhus United 2004, 2005b; energy content fuel oil: JEC 2011
Natural gas	0	kWh / 1000 t RS / year	Schmidt 2007, Kronborg 2006, Aarhus United 2005b; energy consumption of boiler considered as fuel oil
Electricity (external)	38236	kWh / 1000 t RS / year	Schmidt 2007, Kronborg 2006, Aarhus United 2005b; excess electricity of boiler: Energistyrelsen 1995, Aarhus United 2004, 2005b
Electricity mix	EU		Schmidt 2007, Aarhus United 2004, 2005b
Transport			
average distance plantation/oil mill	100	km	Schmidt 2007
Allocation factor after by-products	0.634		

GHG emissions after Oil Mill	1638.42	g CO2eq per kg RSO	Note: Fuel oil is used to produce steam in the power central. Excess electricity from cogeneration is considered as non-used external electricity from grid. The CO2 from oxidation of hexane (direct GWP) is not included in the emission value; this carbon is included in the inventory data of hexane. Only the additional indirect GWP of hexane effluent is applied here.
GHG emissions of Oil Mill	192.52	g CO2eq per kg RefRSO	
GHG emissions of Oil Mill	5.35	g CO2eq per MJ RefRSO	

t.b.c.

Table 7 continued

Refinery	value	unit	source
output			
produced RSO	983.3	t RefRSO / 1000 t RSO / year	Schmidt 2007, Hansen 2006
input			
processed RSO	1000	t RSO / year	reference value
Fuller´s earth	8.9	t / 1000 t RSO / year	Schmidt 2007, Hansen 2006
Energy consumption			
Natural gas	0	kWh / 1000 t RSO / year	Schmidt 2007, Hansen 2006; energy consumption of boiler considered as fuel oil
Fuel oil	7100	l / 1000 t RSO / year	Schmidt 2007, Hansen 2006; energy efficiency of boiler: Energistyrelsen 1995, Aarhus United 2004, 2005b; energy content of fuel oil: JEC 2011
Electricity (external)	24880	kWh / 1000 t RSO / year	Schmidt 2007, Hansen 2006; excess electricity of boiler: Energistyrelsen 1995, Aarhus United 2004, 2005b
Electricity mix	EU		Schmidt 2007, Aarhus United 2004, 2005b
GHG emission after Refinery	**1694.42**	**g CO2eq per kg RefRSO**	Note: Different to IFEU (2011) fuel oil (not natural gas) is used to produce steam in the power central. There is excess electricity from cogeneration which is considered (substracted) as non-used external electricity from grid.
GHG emissions of Refinery	**28.18**	**g CO2eq per kg RefRSO**	
GHG emissions of Refinery	**0.78**	**g CO2eq per MJ RefRSO**	

Transport (to Rotterdam)	value	unit	source
Transport (overland)			
average distance mill/refinery/port	830	km	Falk 2012
vehicle used transporting RefPO	Truck for Diesel		Schmidt 2007
used fuel for vehicle	Diesel		Schmidt 2007
GHG emissions after Transport	**1768.99**	**g CO2eq per kg RefRSO**	
GHG emissions of Transport	**74.57**	**g CO2eq per kg RefRSO**	
GHG emissions of Transport	**2.07**	**g CO2eq per MJ RefRSO**	

Total GHG emissions RefPO	**1768.99**	**g CO2eq per kg RefRSO**	
	49.14	**g CO2eq per MJ RefRSO**	
GHG emission savings compared to fossil comparator (electricity production)	**46.0%**	91 gCO2eq/MJ RED 2009/28/EC	

Esterification	value	unit	source
output			
produced FAME	964.35	t FAME / 1000 t RefRSO / year	Pehnelt and Vietze 2011 (according to WTT Appendix 1 (v3))
Glycerine	101.26	t Glyc. / 1000 t RefRSO / year	Pehnelt and Vietze 2011 (according to WTT Appendix 1 (v3))
input			
processed RefRSO	1000.00	t RefRSO / year	Pehnelt and Vietze 2011 (according to WTT Appendix 1 (v3))
Methanol	106.36	t Meth. / 1000 t RefRSO / year	Pehnelt and Vietze 2011 (according to WTT Appendix 1 (v3))
Phosporic acid (H3PO4)	1.79	t H3PO4 / 1000 t RefRSO / year	Pehnelt and Vietze 2011 (according to WTT Appendix 1 (v3))
Hydrochloric acid (HCl)	19.73	t HCl / 1000 t RefRSO / year	Pehnelt and Vietze 2011 (according to WTT Appendix 1 (v3))
Sodium carbonate (Na2CO3)	2.44	t Na2CO3 / 1000 t RefRSO / year	Pehnelt and Vietze 2011 (according to WTT Appendix 1 (v3))
Sodium Hydroxide (NaOH)	6.64	t NaOH / 1000 t RefRSO / year	Pehnelt and Vietze 2011 (according to WTT Appendix 1 (v3))
Energy consumption			
Natural gas	825102	kWh / 1000 t RefRSO / year	Pehnelt and Vietze 2011 (according to WTT Appendix 1 (v3))
Electricity (external)	71748	kWh / 1000 t RefRSO / year	Pehnelt and Vietze 2011 (according to WTT Appendix 1 (v3))
Electricity mix	EU		Pehnelt and Vietze 2011 (according to WTT Appendix 1 (v3))
Allocation factor after by-products	0.957		
CO2 emissions after Esterification	**2225.85**	**g CO2eq per kg FAME**	
CO2 emissions of Esterification	**470.74**	**g CO2eq per kg FAME**	
CO2 emissions of Esterification	**12.65**	**g CO2eq per MJ FAME**	

Total CO2 emissions FAME	**2225.85**	**g CO2eq per kg FAME**	
	59.83	**g CO2eq per MJ FAME**	
GHG emission savings compared to fossil comparator I (fuel diesel)	**28.6%**	83.8 g CO2eq/MJ RED 2009/28/EC	
GHG emission savings compared to fossil comparator II (fuel diesel)	**31.5%**	87.3 g CO2eq/MJ Silva et al. 2006; CONCAWE et al. 2006	

Table 8: Scenario 6 – Soil acidity and hexane emissions, esterification Weindorf (2008)

Plantation	value	unit	source
output			
yield rape seed (RS) (dried, cleaned)	2697.9	kg RS / ha / year	EU-average 1991-2005: FAOSTAT 2012; drying losses (3%): Jensen et al. 2005.
input			
seed - rape seed (normed)	9	kg seeds / ha / year	Schmidt 2007, Dansk Landbrugsrådgivning 2005a, Nemecek et al. 2003
N-fertiliser	140	kg N / ha / year	Schmidt 2007, Plantedirektoratet 2005a; plantation scheme: Jacobsen et al. 2002
P2O5-fertiliser	57	kg P2O5 / ha / year	Schmidt 2007, Dansk Landbrugsrådgivning 2005a, 2005b
K2O-fertiliser	99	kg K2O / ha / year	Schmidt 2007, Dansk Landbrugsrådgivning 2005a, 2005b
CaO-fertiliser	2000	kg CaO / ha / year	Thamsiriroj and Murphy 2010
Pesticides	0.27	kg ai / ha / year	Dalgaard 2007, Dalgaard et al. 2008
Diesel (all activities and transport)	112.1	l / ha / year	Schmidt 2007, values average of Nemecek et al. 2003, Dalgaard et al. 2001, 2006; no. field work processes: Nemecek et al. 2003, Dalgaard et al. 2001, 2006, Dansk Landbrugsrådgivning 2005a, Jensen et al. 2005
electricity (storage, drying of RS)	60.83	kWh / t RS	Schmidt 2007, Dalgaard et al. 2001, Nemecek et al. 2003
GHG emissions after plantation	**957.77**	**g CO2eq per kg RS**	Note: 167 Kg N/ha N-fertilizer is applied, but 27 kg N/ha can be saved for the crop after rapeseed. Therefore, the 27 kg N/ha is credited to rapeseed. The value of input-seed is normed to convential rapeseed. Diesel consumption including miscellaneaus transport, e.g. inspection of field, with 6.1 l diesel/ha (Dalgaard 2007). Lime (CaO) application to reduce the soil acidity (Thamsiriroj and Murphy 2010).
GHG emissions of plantation	**1473.73**	**g CO2eq per kg RefRSO**	
GHG emissions of plantation	**40.94**	**g CO2eq per MJ RefRSO**	

Oil Mill	value	unit	source
output			
produced Rape Seed Oil (RSO)	418.9	t RSO / 1000 t RS / year	Aarhus United 2005a, Schmidt 2007, efficiency: Oil World 2005
Rape Seed Cake (RSC) (by-product)	563.8	t RSC / 1000 t RS / year	Aarhus United, 2005a, Schmidt 2007, Korning 2006, Kronborg 2006, Hansen 2006
Residual oil content RSC	4	per cent of RSC	Møller et al. 2000
input / hexan-emissions			
processed Rape Seed (RS) per year	1000	t RS per year	reference value
RS losses (drying, washing, transport)	1.7	per cent of RS	Oil World 2005
n-Hexane	498	kg / 1000 t RS / year	Schmidt 2007, Kronborg 2006, Aarhus United 2005a
CO2eq emissions from n-Hexane	2.35	kg CO2eq per t RSO	hexane emissions: Schmidt 2007, Aarhus United 2005a; estimation of CO2eq emissions: IPCC 2007, Collins et al. 2002
Energy consumption			
Fuel oil (light)	21210	l / 1000 t RS / year	Schmidt 2007, Kronborg 2006, Aarhus United 2005b; energy efficiency of boiler: Energistyrelsen 1995, Aarhus United 2004, 2005b; energy content fuel oil: JEC 2011
Natural gas	0	kWh / 1000 t RS / year	Schmidt 2007, Kronborg 2006, Aarhus United 2005b; energy consumption of boiler considered as fuel oil
Electricity (external)	38236	kWh / 1000 t RS / year	Schmidt 2007, Kronborg 2006, Aarhus United 2005b; excess electricity of boiler: Energistyrelsen 1995, Aarhus United 2004, 2005b
Electricity mix	EU		Schmidt 2007, Aarhus United 2004, 2005b
Transport			
average distance plantation/oil mill	100	km	Schmidt 2007
Allocation factor after by-products	*0.634*		
GHG emissions after Oil Mill	**1638.42**	**g CO2eq per kg RSO**	Note: Fuel oil is used to produce steam in the power central. Excess electricity from cogeneration is considered as non-used external electricity from grid. The CO2 from oxidation of hexane (direct GWP) is not included in the emission value; this carbon is included in the inventory data of hexane. Only the additional indirect GWP of hexane effluent is applied here.
GHG emissions of Oil Mill	**192.52**	**g CO2eq per kg RefRSO**	
GHG emissions of Oil Mill	**5.35**	**g CO2eq per MJ RefRSO**	

Refinery	value	unit	source
output			
produced RSO	983.3	t RefRSO / 1000 t RSO / year	Schmidt 2007, Hansen 2006
input			
processed RSO	1000	t RSO / year	reference value
Fuller´s earth	8.9	t / 1000 t RSO / year	Schmidt 2007, Hansen 2006
Energy consumption			
Natural gas	0	kWh / 1000 t RSO / year	Schmidt 2007, Hansen 2006; energy consumption of boiler considered as fuel oil
Fuel oil	7100	l / 1000 t RSO / year	Schmidt 2007, Hansen 2006; energy efficiency of boiler: Energistyrelsen 1995, Aarhus United 2004, 2005b; energy content of fuel oil: JEC 2011
Electricity (external)	24880	kWh / 1000 t RSO / year	Schmidt 2007, Hansen 2006; excess electricity of boiler: Energistyrelsen 1995, Aarhus United 2004, 2005b
Electricity mix	EU		Schmidt 2007, Aarhus United 2004, 2005b
GHG emission after Refinery	**1694.42**	**g CO2eq per kg RefRSO**	Note: Different to IFEU (2011) fuel oil (not natural gas) is used to produce steam in the power central. There is excess electricity from cogeneration which is considered (substracted) as non-used external electricity from grid.
GHG emissions of Refinery	**28.18**	**g CO2eq per kg RefRSO**	
GHG emissions of Refinery	**0.78**	**g CO2eq per MJ RefRSO**	

Transport (to Rotterdam)	value	unit	source
Transport (overland)			
average distance mill/refinery/port	830	km	Falk 2012
vehicle used transporting RefPO	Truck for Diesel		Schmidt 2007
used fuel for vehicle	Diesel		Schmidt 2007
GHG emissions after Transport	**1768.99**	**g CO2eq per kg RefRSO**	
GHG emissions of Transport	**74.57**	**g CO2eq per kg RefRSO**	
GHG emissions of Transport	**2.07**	**g CO2eq per MJ RefRSO**	

Total GHG emissions RefPO	value	unit	source
Total GHG emissions RefPO	**1768.99**	**g CO2eq per kg RefRSO**	
	49.14	**g CO2eq per MJ RefRSO**	
GHG emission savings compared to fossil comparator (electricity production)	**46.0%**	91 gCO2eq/MJ RED 2009/28/EC	

Esterification	value	unit	source
CO2 emissions after Esterification	**2033.11**	**g CO2eq per kg FAME**	Weindorf 2008
CO2 emissions of Esterification	**264.12**	**g CO2eq per kg FAME**	Weindorf 2008
CO2 emissions of Esterification	**7.10**	**g CO2eq per MJ FAME**	Weindorf 2008

Total CO2 emissions FAME	value	unit	source
Total CO2 emissions FAME	**2033.11**	**g CO2eq per kg FAME**	
	54.65	**g CO2eq per MJ FAME**	
GHG emission savings compared to fossil comparator I (fuel diesel)	**34.8%**	83.8 g CO2eq/MJ RED 2009/28/EC	
GHG emission savings compared to fossil comparator II (fuel diesel)	**37.4%**	87.3 g CO2eq/MJ Silva et al. 2006; CONCAWE et al. 2006	

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