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# Quo Vadis European Biofuel Policy: The Case of Rapeseed Biodiesel

By Gernot Pehnelt[*] and Christoph Vietze[**]

## Abstract

The European Union's (EU) Renewable Energy Directive (RED) continues to be the focus of much debate over the validity of biofuel sustainability. The debate is driven in part by ongoing concerns of transparency and regional variations of emissions from feedstock cultivation and processing.

In a working paper, Pehnelt and Vietze (2012) undertook a general analysis of rapeseed biodiesel greenhouse gas (GHG) savings. In light of the recent effort to decentralize assessments to regional (i.e. Member State) authorities to assess the sustainability of biofuel feedstocks, we have done the same for three Member States, incorporating the comments and critique we received on our latest working paper (Pehnelt and Vietze 2012).

Using publicly available cultivation and production figures from Germany (the largest producer and consumer of rapeseed biodiesel), Poland and Romania, we analyse the greenhouse gas (GHG) emissions savings of rapeseed biodiesel which we then compare to the values of GHG savings identified in the RED.

Under average conditions and conservative assumptions on N2O emissions, German rapeseed biodiesel meets the GHG savings requirements of 35 percent in the RED. However, in years with unfavourable weather conditions and lower yields, German rapeseed biodiesel may fail to reach the 35 percent threshold even with efficient production technologies in the subsequent steps of the supply chain. Taking into account higher N2O emissions due to fertilizer input as suggested by some researchers, German rapeseed biodiesel clearly fails to fulfil the 35 percent criterion required by the RED. Meanwhile, in no instance Polish or Romanian rapeseed biodiesel meet the RED's 35% GHG savings threshold.

The assessment of the sustainability of rapeseed biodiesel heavily depends on the very production conditions and assumptions regarding the N2O field emissions. As a matter of fact, not every liter of rapeseed biodiesel produced in the EU is 'sustainable' in the sense of RED. Therefore, the use of standard values (e.g. default values) in order to categorize rapeseed biodiesel – or any other biofuel – as sustainable or not is not justifiable.

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With renewable energy strategies proliferating throughout the world, the validity of technical criteria has become increasingly critical to the success of these strategies – particularly the fiercely debated RED. The application of technical criteria remains inconsistent, and in the case of the RED, resulting in unreliable assessments of biofuel feedstocks and heated debates over the authority of these assessments.

**Keywords**: Biofuel, Rapeseed, Biodiesel, RED, Renewable Energy Directive, Default Values, Typical Values, GHG-emissions

**JEL Code**: F14, F18, O13, Q01, Q15, Q27, Q56, Q57

## 1. Introduction

In a recent working paper titled 'Uncertainties about the GHG Emissions Saving of Rapeseed Biodiesel', Pehnelt and Vietze (2012) show that the sustainability of rapeseed biodiesel in the interpretation of the Renewable Energy Directive (RED) depends heavily on production conditions. The study attracted substantial attention from the scientific community, as well as from the biofuels industry in Europe, and the world of academia. The authors received informed and well-constructed input from many of these actors, building on the approach of the paper. In this new, updated paper we have sought to utilise that peer input to produce a more in-depth and specific analysis, to complement the previous paper. We achieve this by following a more supply-chain specific approach, by using more current data and by adjusting some of the inventory data, though using the same methodological approach as in Pehnelt and Vietze (2012, 2013) which is in line with the methodology proposed by RED.

The calculations in Pehnelt and Vietze 2012 are based on average European values over a period of 15 years and do not distinguish between country specific conditions along the supply chain. Even using average parameters and rather slight parameter variations, the results show a striking range regarding the GHG emissions performance of rapeseed biodiesel and yield a high uncertainty about the actual GHG emissions savings of European rapeseed biodiesel. In most of the scenarios the GHG emissions savings of rapeseed biodiesel do not reach the 35% threshold required by the EU Directive for being considered as a sustainable biofuel.

As a consequence of useful comments on the mentioned working paper, in this study we calculate new scenarios taking into account current input / output data for Germany – the most important producer of rapeseed biodiesel in the EU – Poland and Romania. In further scenarios we address the controversial issue of N2O field emissions which is considered to be one of the critical factors for the assessment of agricultural production with respect to its GHG performance.

As expected, the finding of a high level of uncertainty about the sustainability of rapeseed biodiesel is confirmed by the new calculations. Rapeseed biodiesel produced under current conditions in the EU may reach the 35% threshold which is one of the sustainability criteria of the RED. However, not every single litre of rapeseed biodiesel produced within the EU can be referred to as 'sustainable' under the criteria detailed in RED. Our results suggest that even under efficient production conditions rapeseed biodiesel is rather unlikely to fulfil the advanced sustainability threshold of 50% GHG emissions reduction which will come into force in 2017/2018.

Finally, we briefly outline the consequences of our findings for the EU's future biofuel policy.

## 2. Methodology and Data

This paper is based on Pehnelt and Vietze (2012), but considers more current input / output data on plantation and Transport and the helpful responses from scientists and peer groups to the previous paper. This fruitful scientific discussion has contributed to further strengthening the methodologies and conclusions we are able to reach. Apart from these updated data and assumptions, we rely on the same production process as discussed in Pehnelt and Vietze (2012) and use the inventory data on milling, refinery and esterification specified there. Background data for the whole biodiesel production chain are according to the background data proposed by the Renewable Energy Directive and used by the EU's JRC (see table A-7). In this paper we calculate further scenarios (with IFEU 2011 model) based on different – and more volatile – input / output values as suggested by scientific studies (e.g. Crutzen et al. 2007) as well as the rapeseed industry (e.g. Brünning 2012).

### *2.1 Plantation yields*

In contrast to Pehnelt and Vietze (2012), we include the most current German input / output data in the inventory of the plantation stage, as Germany is the biggest European producer of rapeseed biodiesel. The yield from rapeseed cultivation is the German average 2006-2010 according to FAOSTAT (2012) of 3.82 t/ha (fresh matter content). In two different scenarios we distinguish between high yield and low yield years. Hence, we calculate scenarios with a yield of 3.44 t/ha in 2007 (five year low) and 4.29 t/ha (five year high). As we take accurate calculated values for N2O field emissions into account, we include the rapeseed straw production in our inventory. According to Biograce (2012) the value of (above-ground) straw production yields with 150% of produced rapeseed (dry matter content). While 87% of the produced straw is left in the field, 13% is removed. Accordingly, we calculate with 19.5% removed straw per kg rape seed yield (dry matter content) in our estimations on N2O field emissions. Moreover, the moisture content of rapeseed is (conservatively) calculated with 9% (Schmidt 2007, Dansk Landbrug 2004).

To obtain these higher yields compared to the 1991-2005 average in Pehnelt and Vietze (2012), higher inputs of fertilizer and pesticides are required. Hence, the typical high-yield type of rapeseed used in Germany needs more (especially N)-fertilizer to gain the expected yields. Regarding fertilizers, we use the average (with respect to soil quality) fertilizing recommendations by various sources (e.g. Raiffeisen 2012, LNW 2012, and Nmin-NRW 2012). Hence, 190 Kg N/ha N-fertilizer is applied, but 27 kg N/ha can be saved in the soil for the crop after rapeseed in crop rotation (Schmidt 2007, Jacobsen et al. 2002). Therefore, 27 kg N/ha is credited to rapeseed and we calculate with 163 kg N/ha. Additionally, 85 kg P2O5 per hectare and 200 kg K2O per hectare should be used to receive the above mentioned rapeseed yield.[1] These values regarding the yield / fertilizer ratio are confirmed by experimental field studies

[1] It is agricultural practice to apply lime (CaO) of around 2000 kg per hectare per year to reduce the soil acidity (Thamsiriroj and Murphy 2010) which increase the GHG emissions of plantation. In this paper, we do not consider on this scenario.

conducted in Germany (see Rathke et al. 2005, 2006, Rathke and Diepenbrock 2006). Furthermore, we obtain a pesticide consumption of 2.35 kg a.i. per hectare, the average value suggested by de Vries et al. (2010) and Halleux et al. (2008). The input values for fossil fuel consumption of traction (112.1 l/ha/year) and the drying of rapeseed (60.83 kWh/t rapeseed) are the same as in Pehnelt and Vietze (2012a).

In further scenarios we rely on a typical agricultural system in Poland[2], though assuming comparably efficient production conditions on the subsequent production steps. Due to the local cultivation methods, varieties and climate conditions rapeseed plantations gain lower yields than in Germany where the highest yields per hectare are obtained. The average yield per hectare in Poland in the period observed (2006-2010) is about 2.77 t/ha fresh matter content (FAOSTAT 2012). We use the fertilizer values suggested by Firrisa (2011). According to this study, a fertilizer input of 183 kg N, 157 kg P2O5 and 132 kg K2O per hectare is considered. As in all scenarios we use conservative values and, therefore, credit 27 kg N/ha to rapeseed which can be saved in the soil for the succession crop in a crop rotation system. Hence, we calculate with 156 kg N/ha. Following de Vries et al. (2010) and Halleux et al. (2008), we rely on the same pesticide usage (2.35 kg ai/ha) as in the other scenarios.

In addition, we calculate some scenarios for Romania which rely on a typical extensive agricultural system resulting in comparatively lower yields. On the other hand, such plantings require far lower fertilizer input and diesel consumption for traction. Moreover, due to local climate conditions the seeds do not have to be dried after harvesting. Thus, no drying is considered in the study of Romanian rapeseed biodiesel. According to FAOSTAT (2012) Romanian rapeseed plantations yield a five year average (2006-2011) of 1.59 t/ha (fresh matter). As input / output data on Romanian rapeseed plantations are not readily available, we use the values of two studies by Baquero et al. (2011, 2013) regarding extensive Spanish rapeseed planting. These studies rely on similar climatic and technical conditions and should be comparable to Romanian conditions. According to Baquero et al. (2011, 2013), a fertilizer input of 115 kg N, 125.9 kg P2O5 and 55.5 kg K2O per hectare is considered. As in all scenarios we use conservative values and, therefore, credit 27 kg N/ha to rapeseed which can be saved in the soil for the succession crop in a crop rotation system. Hence, we calculate with 88 kg N/ha. Furthermore, a lower (normed) seed input of 6.13 kg seeds per hectare and a lower fossil fuel consumption of 70.0 l/ha for traction is applied. Following de Vries et al. (2010) and Halleux et al. (2008), we rely on the same pesticide usage (2.35 kg ai / ha) as in the other scenarios.

### *2.2 Fertilizer use and N2O field emissions*

Intensive agricultural cultivation produces most of the GHG emissions in the biodiesel production chain. Besides the CO2eq emissions arising from land management, the production of pesticides and for sowing, harvesting and transport; especially the production

[2] In general, the Eastern European rapeseed system is characterized by a more extensive cultivation (including lower fertilizer input) resulting in a lower crop output per hectare.

and application of N-fertilizers could result in such high emissions of greenhouse gases which are estimated to be worse than for conventional diesel (Reijnders and Huijbregts 2008).

The production of N-fertilizers in the Haber-Bosch process has increased by over 800% in the past 50 years (Haberl et al. 2012, Foley et al. 2011). Although, the GHG emissions from the fossil energy requirement of N2 formation and N2 reduction increased somewhat less because of the higher process efficiency (Haberl et al. 2012), more than 1% of the global primary energy is consumed in this process (Schulze et al. 2010).

However, through the implementation of new production technologies a further reduction of energy input and resulting CO2 emissions in the fertilizer production is possible (Jenssen and Kongshaug 2003). Therefore, significant potential for GHG emissions reduction in the whole process may be achieved by using the best available technology in fertilizer production.

Direct and indirect GHG-emissions due to N2O field effluents from N-fertilizers are very important when it comes to the GHG performance of agriculture. With a 298 fold global warming potential[3], N2O has a much higher potential greenhouse effect than CO2 (default value in RED (EU 2009)). Human activities are supposed to be responsible for about 30% of the global N2O emissions. According to Wuebbles (2009), the largest human related N2O source (67%) comes from agricultural practices and activities, including the production of nitrogen-fixing crops and the use of synthetic and organic fertilizers (application of livestock manure to plantation).

The size of the biogenic N2O emissions is subject to considerable debate (Reijnders and Huijbregts 2008). These emissions occur irrespective of whether the applied form of nitrogen is organic (manure, harvest residue biological fixation) or inorganic N (artificial fertilizer) (Haberl et al. 2012). According to Davidson (2009), approximately 2% to 3% of the applied N-fertilizers and N in crop residues (straw) will end up as N2O that escapes into the atmosphere. The N2O emission factor (expressed as mass of N: N2O_N) is the percentage of N as fertilizer or biologically fixed N emitted as N2O includes direct N2O emissions from N and additions from mineral fertilisers, organic amendments and crop residues and N mineralised from mineral soil as a result of loss of soil carbon following land use change[4], as well as indirect N2O emissions from atmospheric deposits of N on soils and water surfaces volatilised as NH3 or NOx and N2O emissions from N leaching and runoff as nitrate (IPCC 2011). This overall factor is estimated to be between 1.18 % (Bouwman et al. 2002) and 5% of applied N-fertilizers and N in crop residues (Crutzen et al. 2007, 2008, Smith 2012), with the IPCC's (2006) estimates (1.3%) ranging at the lower bound.

Mosier et al. (1998) estimate that direct N2O emissions from agricultural fields planted with European rapeseed and Brazilian soybeans may be about 1.25% of added fixed nitrogen. They argue that fixed nitrogen lost from agricultural fields is also subject to additionally

[3] Some sources suggest a global warming potential of N2O that is more than 300 times higher than the global warming potential of CO2.

[4] Land use chance is not considered here.

microbial conversion to N2O (estimated at 2.5% of fixed N lost). In sum the resulting N2O emission factor is estimated with 3.75% of fixed (fertiliser plus crop residues) nitrogen. Lower global mean nitrogen field emissions are estimated by Bouwman et al. (2002) with 0.9 % N2O and 0.7% NOx emissions of applied N summing up to 1.18% N2O_N (N-mass in N2O) emissions per applied N in fertilizers and crop residues.

According to Reay et al. (2012) the direct and indirect emission estimates by the IPCC (2006) do not cover subsequent recycling of the added nitrogen and resulting N2O emissions. Instead these are covered by additional IPCC emission factors such as those for crop residues, manure and sewage nitrogen. More current estimates by Crutzen et al. (2007, 2008) and Smith et al. (2012) taking a different approach ('top-down') suggest that the combined direct and indirect emission are rather 3 to 5% of the fixed nitrogen added. However, there is some uncertainty since local conditions may significantly affect local conversion rates (Mosier et al. 1998, Reijnders and Huijbregts 2008).[5]

Hence, in most of our calculations, we use the same methodology and standard values as the IPCC (2006); calculated with the Biograce (2012) model.

First, we use the emission factor for direct N2O field emissions (EF1) of 1.00 per cent N2O emissions (calculated as N-mass in N2O: N2O_N) per kg N additions from N-fertilisers (synthetic or organic) and N-content of crop residues (IPCC 2006). Thus, EF1 refer to the fraction of all added N that is lost directly as N2O (estimated as N2O_N) per kg N applied as N-fertilizer and crop residues (and N mineralised from mineral soil as a result of loss of soil carbon due to LUC).

Second, the emission factor for NH3 and NOx volatilization (EF4) of 1.00 per cent N2O_N per kg N deposited from NH3 or NOx (10% of N from synthetic, 20% from organic N-fertiliser) is applied. More precisely, this emission factor accounts for the N2O_N that is atmospherically deposited from volatized NH3. The fraction of synthetic fertiliser N that volatilises as NH3 and NOx is expected as 10% N-mass volatilised as NH3 per kg of N applied as synthetic N-fertilizer and 20% per kg organic fertilizer (IPCC 2006).[6] Hence, an additional fraction of 0.1% of the applied synthetic N-fertilizer (0.2% of organic N-fertilizer) effluents as N2O (calculated as N-mass content).

Third, we use an emission factor (EF6) for nitrate leaching and runoff of 0.75 per cent N2O_N per kg N leached and runoff as nitrate (30% of N from N-fertilizers and crop residues). This emission factor measures the N2O_N emissions from leached nitrate. The fraction of all added N from (synthetic and organic) fertilizers, N-mass in crop residues and soil mineralization that is lost through leaching and runoff as nitrate is expected as 30% N-mass leached as nitrate per kg of applied / mineralised N (IPCC 2006). Thus, an additional fraction

[5] A measure to reduce N2O and NOx field emissions could be the use of enhanced-efficiency fertilizers (i.e. nitrification inhibitors and polymer-coated fertilizers) (Akiyama et. al. 2010).

[6] This denote that using organic fertilizers like needs no prime energy input in fertilizer production, but results in higher (indirect) N2O field emissions.

of 0.225% of all added N-mass (fertilizer and N in crop residues) effluents as N2O (calculated as N-mass content) will be included in our estimation. In sum, the N2O emissions regarding the applied N in fertilizers and crop residues are estimated with 1.3% N2O_N (N-mass in N2O) per added N in the baseline scenario.

Additionally, as suggested by Crutzen et al. (2007, 2008) and Smith (2012) we estimate some scenarios taking alternative – and maybe more realistic – N2O field emissions into account. Moreover, some researchers of IPCC (2011) assume that the default values do not account for the observed atmospheric increase of N2O, so that the ranges of default emission factors are logarithmic: e.g., EF1 = 1% (range 0.3-3.0%). Following these suggestions, we calculate further scenarios with higher N2O-field emission factors. In some scenarios we use the upper bound of emission factors as suggested by IPCC (2006). Hence, 3% as EF for direct N2O field emissions, 5% as EF for NH3 volatilization, and 2.5% EF for nitrate leaching and runoff are applied; adding up to 4.1% N2O_N emissions per kg applied N-mass in fertilizers and crop residues. In further scenarios the halve of the IPCC (2006) maximum emission factors is used: 1.5% EF for direct N2O field emissions, 2.5% EF for NH3&NOx volatilization, and 1.25% EF for nitrate leaching and runoff. The outcome of these values is an overall emission factor of 2.0% per kg added N-mass. Depending on the very conditions in the field, lower N2O field emissions may occur in case of ideal weather conditions and perfect soils (Brentrup and Pallière 2008) with adjusted field management (e.g. ploughing just after fertilizing). Hence, we calculate additional scenarios with 80% of the IPCC (2006) standard emission factors: 0.8% EF for direct N2O field emissions, 0.8% EF for NH3&NOx volatilization, and 0.6% EF for nitrate leaching and runoff; adding up to an overall emission factor of 1.0% per kg added N-mass.

Again, it should be noted that in each scenario 27 kg N-fertilizer of the applied input is credited in the plantation step, as some N-mass in the soil and crop residues can be used for the following crops in a rotation scheme. The 27 kg N-credit correspond to a GHG emissions credit of 3.14 g CO2eq / MJ FAME (not allocated) at the plantation step. As a result, our values estimated regarding the N-fertilizer production and N2O field emissions represents the lower band of most scientific assumptions. It should be noted that perennial woody coppice species (e.g. oil palm) have more favourable climate impacts (Crutzen et al. 2007), as these crops have a lesser N demand. Thamsiriroj and Murphy (2009) show that oilseed rape requires 147.4% of the fertilizer input (per energy output) to grow respective to oil palm. This is due to the fact that oilseed rape needs annual fertilizer not only for the fruit but also to emerge roots and trunks, whereas perennial crop species need fertilizers solely to build fruits and new leaves.

### *2.3 Milling and Refinery*

Different to Pehnelt and Vietze (2012), we do not consider hexane emissions in the milling stage, as the successional CO2eg emissions are rather minor. Moreover, hexane emissions in the production step are prohibited by German environmental law. However, such emissions

may still occur. Whereas a minor share comes from storage tanks, a considerable share of the hexane input goes with the rapeseed meal to final processing and effluent during this process (Schmidt 2007).

At the refinery stage we do not change inventory data compared to Pehnelt and Vietze (2012), as the total GHG emissions of the refinery step assumed in Pehnelt and Vietze (2012) have been already below the standard value suggested by the JRC (EU 2009). The deodorization step has only been part of the description of production process in the above mentioned paper, but is not part of there inventory data because it is not necessary for the production of biodiesel.[7]

### *2.4 Transport*

In our more supply-chain specific calculations we have also adjusted the inventory of the transportation stage. Thus, it is assumed that the rapeseed oil refined in Germany, Poland, or Romania respectively is transported to final consumption for (co-generated) electricity production or further processing to FAME / biodiesel within Europe (Schmidt 2007). Following our conservative approach, in case of German rapeseed oil we calculate shorter transport distances as most of the German rapeseed oil is intended to be refined and used in Germany. However, since crude oil has to be transported from the field / mill to the subsequent production facilities and – not least – the final product (FAME) has to be transported to the very fuel station, it is rather unlikely that most of the transport takes place by ship which has been suggested in comments by the industry (e.g. Brankatschk 2012, Brünning 2012) on Pehnelt and Vietze (2012).

Hence, we assume transportation in a diesel truck averaging about 350 km.[8] The resulting CO2eq emissions (0.87 g CO2eq per MJ RefRSO) are below the standard values (1.0 g CO2eq per MJ RefRSO) suggested by the EU (2009).

In our scenarios of Polish rapeseed plantation system we calculate a diesel truck transport distance of 300 km from the geographic centre of Poland to the Port Gdansk (Falk 2012), followed by a 1,500 km distant ship transport (Fuel oil Tanker 50kt) to the Port of Rotterdam (PortWorld Distances 2012).

In the case of the Romanian scenarios a diesel truck transport distance of 615 km from the geographic centre of Romania to the Port of Constanţa (Falk 2012), followed by a 6,150 km distant ship transport (Fuel oil Tanker 50 kt) to the Port of Rotterdam (PortWorld Distances 2012) is applied. This is plausible since 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.

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7 Note: The whole discussion is rather of academic nature since these adjustments have a very small impact on the overall result since the refinery step accounts for roughly one per cent of the total GHG emissions of rapeseed biodiesel.

8 This equals the distance between the geographic center of Germany to the Port of Hamburg (Falk 2012), where huge production facilities for FAME are located.

## 3. Results

In order to provide the highest possible transparency we calculate and publish the GHG emissions of every step of the rapeseed biodiesel production chain and provide a list of all inputs used in our calculations and corresponding data sources. 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 transportation biodiesel (FAME) according to RED and by using common esterification technologies. This is why we present three GHG emission saving values regarding the respective fossil fuel comparator. We calculate two values for the GHG emissions saving potential.

First, we compare the GHG emissions of rapeseed biodiesel to the emission value of fossil diesel as stated by the EU-Directive (EU 2009). Second, we calculate values for the GHG saving potential of rapeseed biodiesel to current LCA of fossil fuel emissions, as applied by Silva et al. (2006) and CONCAWE et al. (2006).

In sum we calculate 28 scenarios regarding Germany, Poland and Romania distinguishing between different N2O field emissions and esterification methodologies respectively.

In scenario 1 (Table 1), we use the average yield in Germany in the period 2006-2010. As in all scenarios, the energy content of rapeseed cake and glycerine is considered as a by-product.[9] For esterification, the EU's standard value of the accordant GHG emissions is applied in scenario 1. The results of scenario 1 indicate that GHG emissions savings of German rapeseed biodiesel are around the EU's 35% threshold. More precisely, the GHG emissions of the production of rape biodiesel (FAME) is estimated with 55.12 g CO2eq per MJ FAME resulting in an GHG emission saving value of 34.2% compared with the RED (EU 2009) fossil fuel comparator and in an saving value of 36.9% according current comparator of fossil fuel emissions (Silva et al. 2006) and CONCAWE et al. 2006).

[9] Note: This allocation method is rather in favor of rapeseed biodiesel. Other application methodologies (e.g. economic value) may create less favorable results.

# Table 1: Scenario 1 – German average, Esterification EU (2009)

| Plantation | value | unit | source |
|---|---|---|---|
| ***output*** | | | |
| yield rape seed (RS) (fresh matter) | 3823.5 | kg RS / ha / year | German-average 2006-2010: FAOSTAT 2012 |
| moisture content in rape seed | 9.0 | per cent of RS | Schmidt 2007, Dansk Landbrug 2004 |
| straw removed from field | 678.4 | kg straw / ha / year | ratio of straw production (150% of dry matter RS yield): Biograce 2012; ratio of straw removed from field (13% of produced straw): Schmidt 2007 |
| ***input*** | | | |
| seed - rape seed (normed) | 9.0 | kg seeds / ha / year | Schmidt 2007, Dansk Landbrugsrådgivning 2005a, Nemecek et al. 2003 |
| N-fertiliser | 163.0 | kg N / ha / year | Raiffeisen 2012 (average); N-credit for crop rotation: Schmidt 2007, Jacobsen et al. 2002 |
| P2O5-fertiliser | 85.0 | kg P2O5 / ha / year | Raiffeisen 2012 (average) |
| K2O-fertiliser | 200.0 | kg K2O / ha / year | Raiffeisen 2012 (average) |
| CaO-fertiliser | 0 | kg CaO / ha / year | |
| Pesticides | 2.35 | kg ai / ha / year | de Vries et al. 2010, Halleux 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 |
| ***Emission factors N2O-field emissions*** | | | |
| EF for direct N2O field emissions | 1.00 | per cent N2O_N / kg N additions from N-fertilisers and crop residues | IPCC 2006, fraction of all added N that is lost directly as N2O per kg N applied as N-fertilizer and crop residues |
| EF for NH3&NOx volatilization | 1.00 | per cent N2O_N / kg N deposited as NH3 or NOx (10% of N from synthetic N-fertiliser) | IPCC 2006, fraction of synthetic fertiliser N that volatilises as NH3 and NOx is expected as 10% N-mass volatilised as NH3&Nox per kg of N applied as synthetic N-fertilizer (IPCC 2006) |
| EF for Nitrate leaching and runoff | 0.75 | per cent N2O_N / kg N leached and runoff as nitrate (30% of N from N-fertilizers and crop residues) | IPCC 2006, fraction of all added N that is lost through leaching and runoff as nitrate is expected as 30% N-mass leached as nitrate per kg of N applied as N-fertilizer and crop residues (IPCC 2006) |
| **GHG emissions after plantation** | **813.49** | **g CO2eq per kg RS** | Note: 190 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 (alloc.)** | **1227.82** | **g CO2eq per kg RefRSO** | |
| **GHG emissions of plantation (alloc.)** | **34.11** | **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*** | | | |
| 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 |
| ***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* | *0.622* | | |
| **GHG emissions after Oil Mill** | **1387.90** | **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 (alloc.)** | **183.66** | **g CO2eq per kg RefRSO** | |
| **GHG emissions of Oil Mill (alloc.)** | **5.10** | **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** | **1439.65** | **g CO2eq per kg RefRSO** | Note: The inventory date do not include deodorisation. 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 (alloc.)** | **28.18** | **g CO2eq per kg RefRSO** | |
| **GHG emissions of Refinery (alloc.)** | **0.78** | **g CO2eq per MJ RefRSO** | |

| Transport (to Hamburg) | value | unit | source |
|---|---|---|---|
| ***Transport (overland)*** | | | |
| average distance mill/refinery/port | 350 | km | Distance Niederdorla (geographic center Germany) - Port Hamburg, Germany: Falk 2012 |
| vehicle used transporting RefPO | Truck for Diesel | | Schmidt 2007 |
| used fuel for vehicle | Diesel | | Schmidt 2007 |
| **GHG emissions after Transport** | **1471.09** | **g CO2eq per kg RefRSO** | |
| **GHG emissions of Transport (alloc.)** | **31.44** | **g CO2eq per kg RefRSO** | |
| **GHG emissions of Transport (alloc.)** | **0.87** | **g CO2eq per MJ RefRSO** | |

| | | |
|---|---|---|
| **Total GHG emissions RefPO** | **1471.09** | **g CO2eq per kg RefRSO** |
| | **40.86** | **g CO2eq per MJ RefRSO** |
| **GHG emission savings compared to fossil comparator (electricity production)** | **55.1%** | 91 gCO2eq/MJ<br>RED 2009/28/EC |

**t.b.c.**

**Table 1: Scenario 1 (continued)**

| Esterification EU | 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)) |
| Phosphoric 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** | **2050.43** | **g CO2eq per kg FAME** |
| **CO2 emissions of Esterification (ac.)** | **626.51** | **g CO2eq per kg FAME** |
| **CO2 emissions of Esterification (ac.)** | **16.84** | **g CO2eq per MJ FAME** |

| | | |
|---|---|---|
| **Total CO2 emissions FAME** | **2050.43** | **g CO2eq per kg FAME** |
| | **55.12** | **g CO2eq per MJ FAME** |
| **GHG emission savings compared to fossil comparator I (fuel diesel)** | **34.2%** | 83.8 g CO2eq/MJ<br>RED 2009/28/EC |
| **GHG emission savings compared to fossil comparator II (fuel diesel)** | **36.9%** | 87.3 g CO2eq/MJ<br>Silva et al. 2006; CONCAWE et al. 2006 |

Using more current production values for the transesterification stage (WTT Appendix 1 (v3) according to Pehnelt and Vietze 2013) the GHG emission savings of rapeseed diesel turn more in favour: In scenario 2 (table A-1) the GHG emission savings of rape diesel lie between 38.1% and 40.6% respectively. In this case German rapeseed biodiesel easily reaches the EU 35% threshold, but – however – still fails to reach the 50 % threshold which will enter into force in 2017.

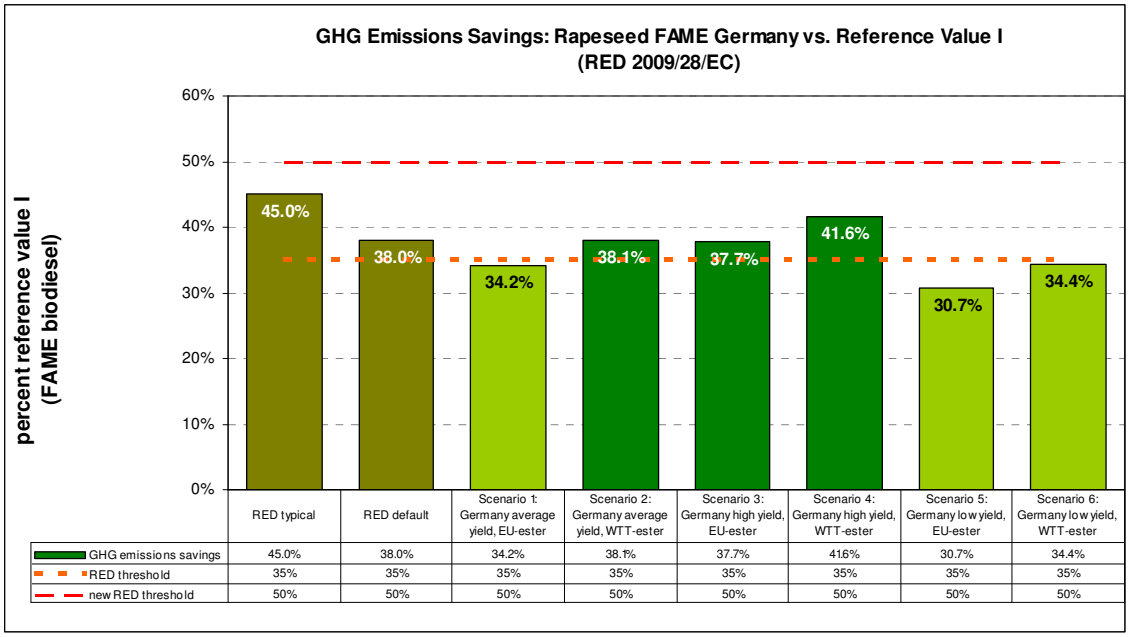
More interestingly, we evaluate the variance of the German rapeseed yields. Using the five year high (4286.7 kg RS/ha/year in 2009) and low (3436.6 kg RS/ha/year in 2007) of German rapeseed plantation yields we gain rather mixed results. The GHG emission savings values ranging between 30.7 % (scenario 5, low plantation yields, esterification step and fossil fuel comparator according RED EU (2009)) and 44.0% (scenario 4, high plantation yields, WTT (Pehnelt and Vietze 2013) esterification step, and fossil fuel comparator according Silva et al. (2006) and CONCAWE et al. (2006)).

**Table 2: GHG emissions of German rapeseed FAME**

| Scenario No | GHG emissions (g CO2eq per MJ rape FAME) | | | | | | GHG emissions savings rape FAME | |
|---|---|---|---|---|---|---|---|---|
| | Plantation | Oil mill | Refinery | Transport | Esterification | total FAME | % reference value I (RED) | % reference value II |
| Scenario 1: Germany average yield, EU-ester | 31.95 | 4.78 | 0.73 | 0.82 | 16.84 | 55.12 | **34.2%** | **36.9%** |
| Scenario 2: Germany average yield, WTT-ester | 32.75 | 4.90 | 0.75 | 0.84 | 12.65 | 51.89 | **38.1%** | **40.6%** |
| Scenario 3: Germany high yield, EU-ester | 29.10 | 4.73 | 0.73 | 0.82 | 16.84 | 52.22 | **37.7%** | **40.2%** |
| Scenario 4: Germany high yield, WTT-ester | 29.82 | 4.85 | 0.75 | 0.84 | 12.65 | 48.92 | **41.6%** | **44.0%** |
| Scenario 5: Germany low yield, EU-ester | 34.88 | 4.83 | 0.73 | 0.82 | 16.84 | 58.11 | **30.7%** | **33.4%** |
| Scenario 6: Germany low yield, WTT-ester | 35.76 | 4.95 | 0.75 | 0.84 | 12.65 | 54.95 | **34.4%** | **37.1%** |

Our estimations show a volatility of 43.3% between best and worse conditions and the resulting plantation yields and emission savings. However, even in the best case the 50% threshold entering into force in 2017 is not reached. See table 2 and figure 1 and 2 for a comparison of German rapeseed diesel.

**Figure 1: GHG emissions savings of German rapeseed FAME**



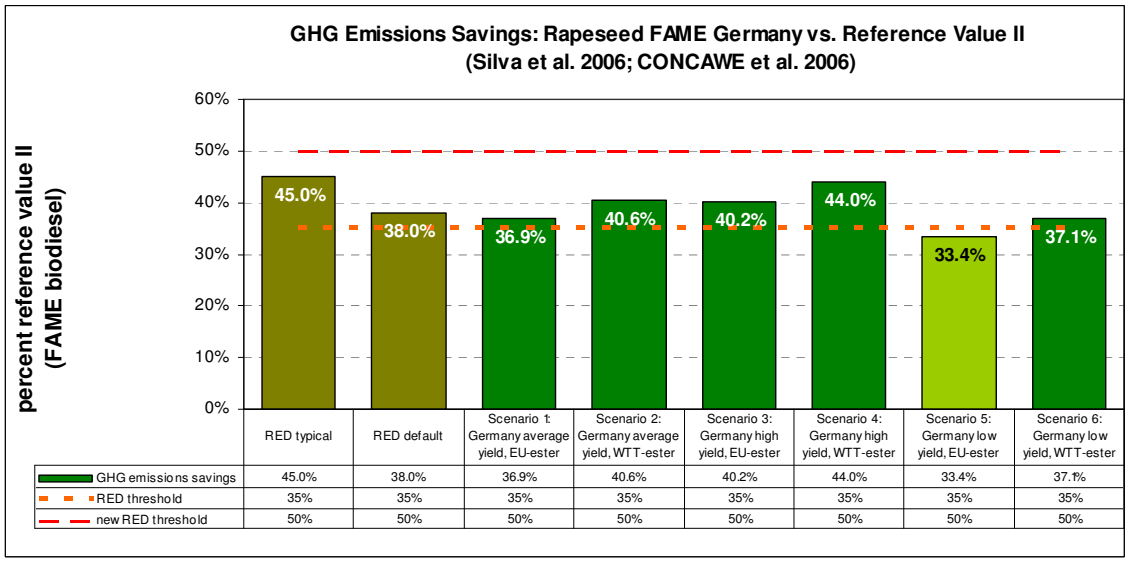
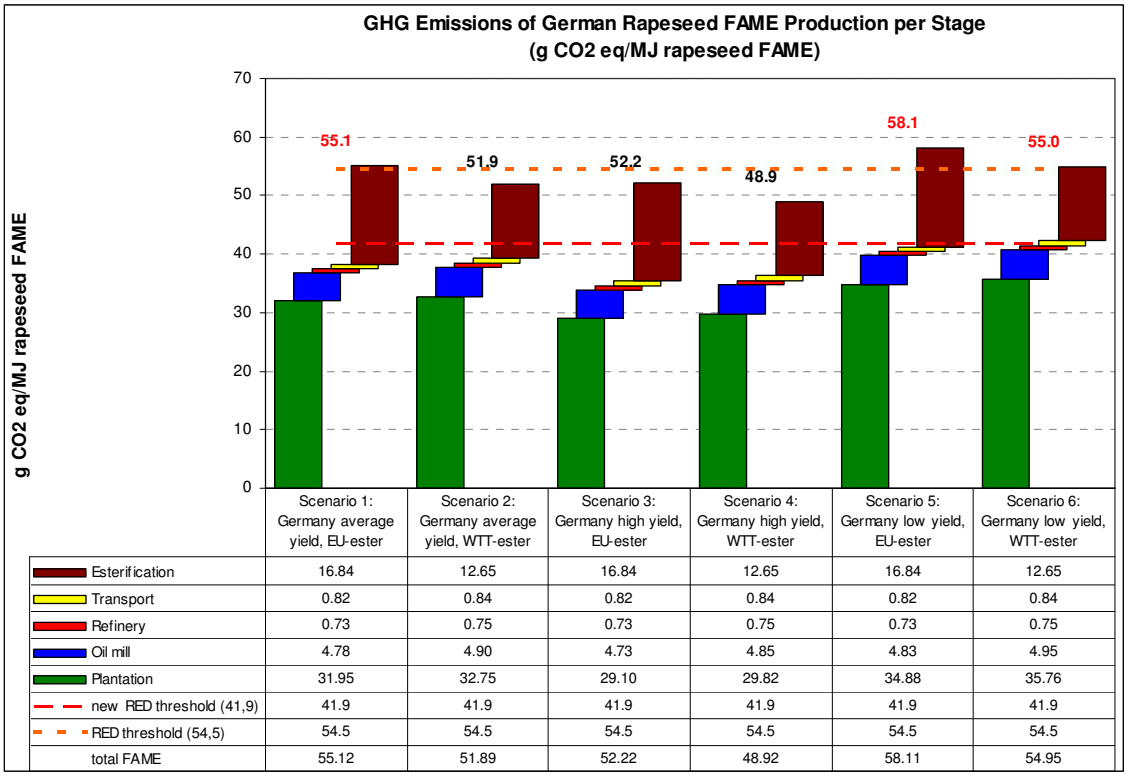



**Figure 2: GHG emissions of German rapeseed FAME**



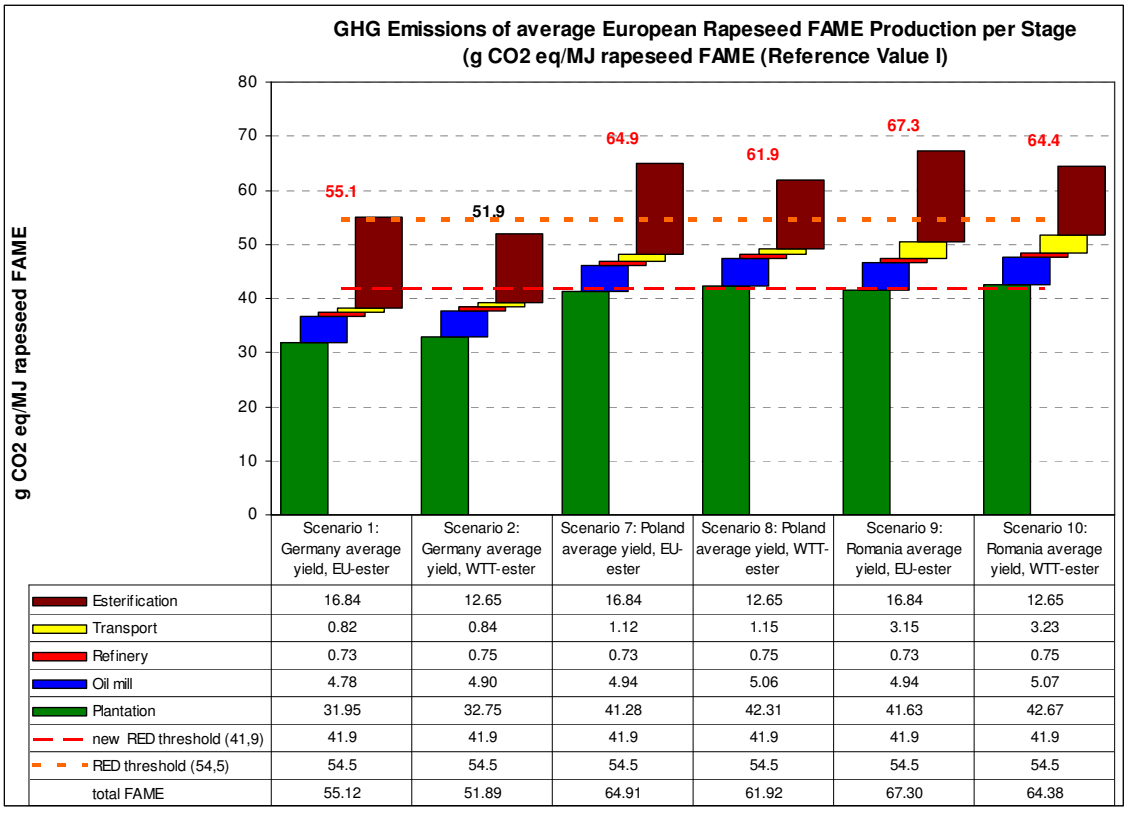

| | Scenario 1: Germany average yield, EU-ester | Scenario 2: Germany average yield, WTT-ester | Scenario 3: Germany high yield, EU-ester | Scenario 4: Germany high yield, WTT-ester | Scenario 5: Germany low yield, EU-ester | Scenario 6: Germany low yield, WTT-ester |
|---|---|---|---|---|---|---|
| Esterification | 16.84 | 12.65 | 16.84 | 12.65 | 16.84 | 12.65 |
| Transport | 0.82 | 0.84 | 0.82 | 0.84 | 0.82 | 0.84 |
| Refinery | 0.73 | 0.75 | 0.73 | 0.75 | 0.73 | 0.75 |
| Oil mill | 4.78 | 4.90 | 4.73 | 4.85 | 4.83 | 4.95 |
| Plantation | 31.95 | 32.75 | 29.10 | 29.82 | 34.88 | 35.76 |
| new RED threshold (41,9) | 41.9 | 41.9 | 41.9 | 41.9 | 41.9 | 41.9 |
| RED threshold (54,5) | 54.5 | 54.5 | 54.5 | 54.5 | 54.5 | 54.5 |
| total FAME | 55.12 | 51.89 | 52.22 | 48.92 | 58.11 | 54.95 |

In further scenarios, we assess the GHG emissions from Polish rapeseed. Using the five-year average of Polish rapeseed FAME production using assumptions on the GHG emissions of the esterification process according to the EU (2009) (scenario 7, table A-2), we obtain an emission saving value of 22.5% and 25.6% respectively, depending on the fossil fuel estimator. When relying on WTT esterification technology (scenario 8, table A-2) somewhat better results can be reached (26.1% fossil comparator I; and 29.1 % fossil comparator II). In none of the scenarios for Poland the threshold of 35% is reached by rapeseed biodiesel.

Simulating a supply-chain starting with Romanian rapeseed plantation (table A- 3), emission saving values fall far below the 35% threshold. Even when calculating with modern esterification technologies (scenario 9) the GHG emissions saving values are 23.2% (comparator I) and 26.3% (comparator II). Using the esterification values according to the EU (2009) as done in scenario 10, the GHG emission saving decline to 19.7% compared to the fossil fuel comparator according to RED (EU 2009). When comparing with fossil fuel emissions as suggested by Silva et al. (2006) and CONCAWE et al. (2006) the results are slightly better but still way below the 35% threshold.

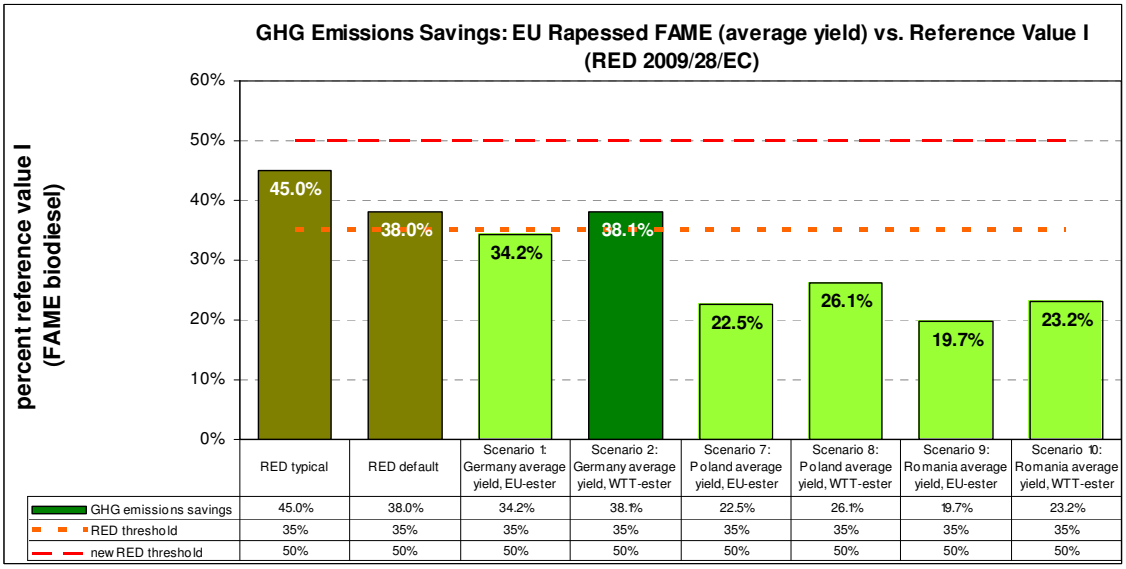
Figure 3 gives a comparison of the average European results regarding GHG emissions per MJ produced rapeseed. The resulting emissions saving values depending on the fossil fuel comparator are displayed in figure 4.

**Figure 3: GHG emissions of rapeseed FAME – comparison Germany, Poland and Romania (5-year average)**




| | Scenario 1: Germany average yield, EU-ester | Scenario 2: Germany average yield, WTT-ester | Scenario 7: Poland average yield, EU-ester | Scenario 8: Poland average yield, WTT-ester | Scenario 9: Romania average yield, EU-ester | Scenario 10: Romania average yield, WTT-ester |
|---|---|---|---|---|---|---|
| Esterification | 16.84 | 12.65 | 16.84 | 12.65 | 16.84 | 12.65 |
| Transport | 0.82 | 0.84 | 1.12 | 1.15 | 3.15 | 3.23 |
| Refinery | 0.73 | 0.75 | 0.73 | 0.75 | 0.73 | 0.75 |
| Oil mill | 4.78 | 4.90 | 4.94 | 5.06 | 4.94 | 5.07 |
| Plantation | 31.95 | 32.75 | 41.28 | 42.31 | 41.63 | 42.67 |
| new RED threshold (41,9) | 41.9 | 41.9 | 41.9 | 41.9 | 41.9 | 41.9 |
| RED threshold (54,5) | 54.5 | 54.5 | 54.5 | 54.5 | 54.5 | 54.5 |
| total FAME | 55.12 | 51.89 | 64.91 | 61.92 | 67.30 | 64.38 |

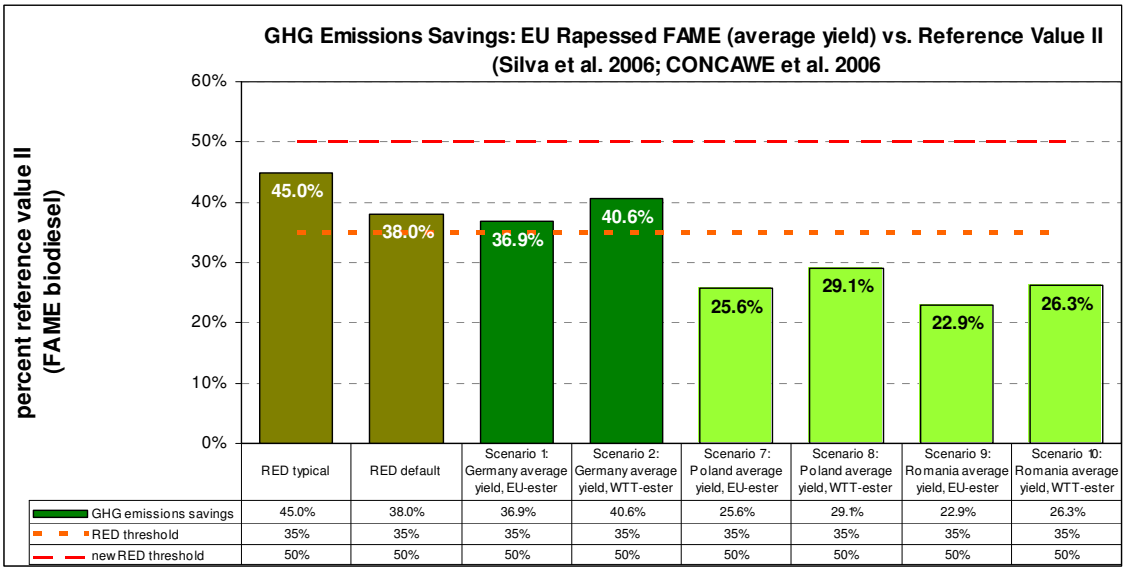
**Figure 4: GHG emissions savings of rapeseed FAME – comparison Germany, Poland and Romania (5-year average) and fossil fuel comparator**




| | RED typical | RED default | Scenario 1: Germany average yield, EU-ester | Scenario 2: Germany average yield, WTT-ester | Scenario 7: Poland average yield, EU-ester | Scenario 8: Poland average yield, WTT-ester | Scenario 9: Romania average yield, EU-ester | Scenario 10: Romania average yield, WTT-ester |
|---|---|---|---|---|---|---|---|---|
| GHG emissions savings | 45.0% | 38.0% | 34.2% | 38.1% | 22.5% | 26.1% | 19.7% | 23.2% |
| RED threshold | 35% | 35% | 35% | 35% | 35% | 35% | 35% | 35% |
| new RED threshold | 50% | 50% | 50% | 50% | 50% | 50% | 50% | 50% |

**t.b.c**

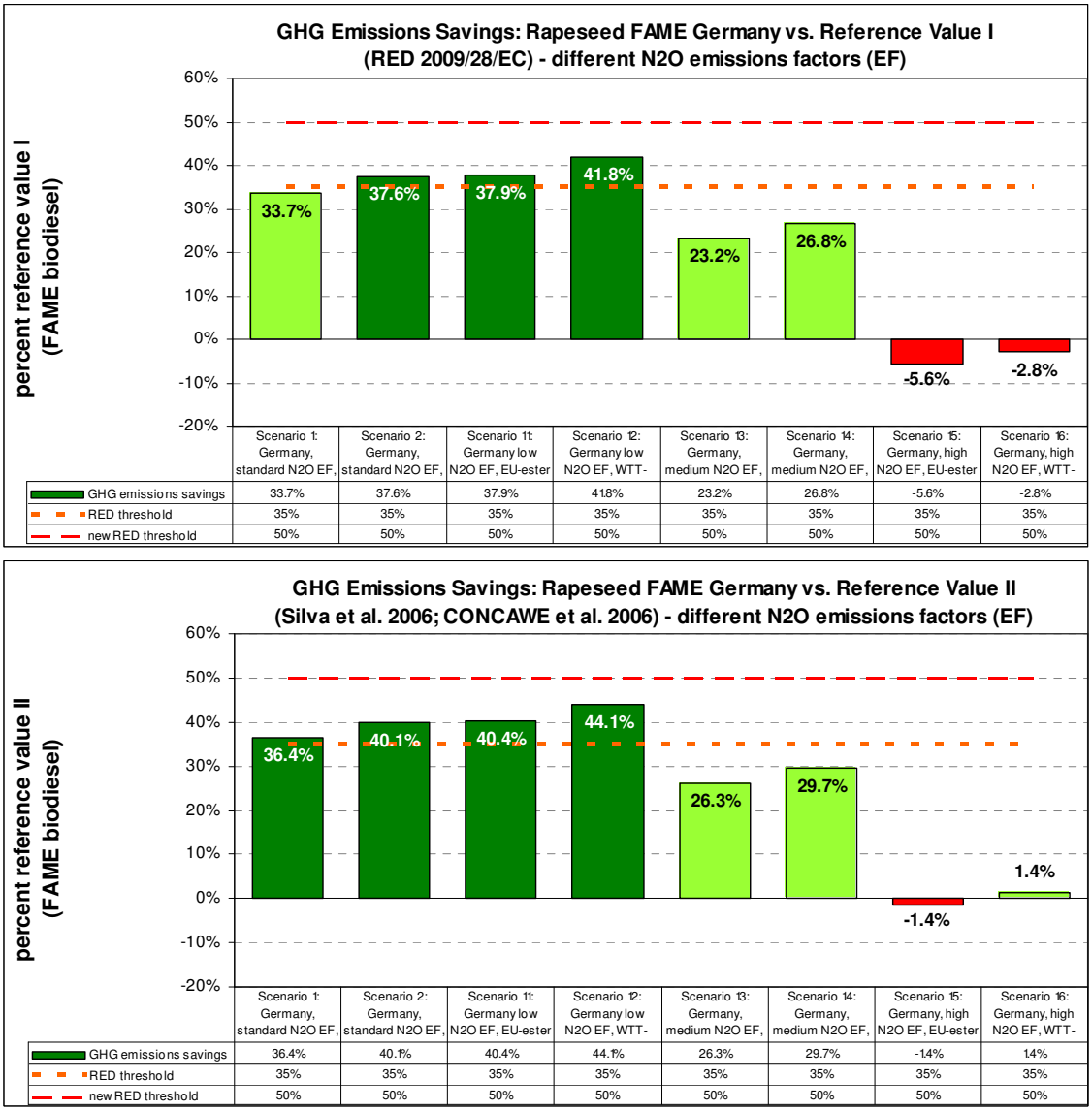
**Figure 4 continued**




In a further step we investigate the effect of different N2O field emissions. As further explained in our methodology section, N2O field emissions estimates according to IPCC (2006) currently in use are widely criticised by other research papers. Following these criticisms and taking the wide range of possible variations into account we gain a tremendous range of results regarding the GHG emissions savings. Hence, we calculate four different scenarios for rapeseed cultivation in Germany, Poland and Romania respectively. Relying on very good soil and whether conditions in connection with perfect field management we derive scenarios with 80% of the IPCC (2006) N2O field emissions estimates. Beside our average scenarios (strictly according to IPCC 2006), we calculate scenarios with the maximum (high N2O EF) and with semi-maximum N2O field emissions (medium N2O EF) as suggested by IPCC (2006). The last scenario is closer to current research findings on N2O field emissions (e.g. Crutzen et al. 2007, 2008; Smith 2012) and the comments we received.

Our calculations (see table A-4) show a broad range of results. Precisely, regarding Germany our results on GHG emission savings are ranging from a clear fulfilment of the RED threshold (low N2O EF) to even slightly negative values (high N2O EF). The results are ranging from 44.12% GHG emissions saving if considering 80% of the standard N2O emissions factor suggested by IPCC (2006 (WTT-esterification and fossil fuel comparator II) to -5.6% GHG emission saving if considering the maximum possible N2O field emissions according IPCC (2006) (EU-esterification, fossil fuel comparator I). See figure 5 for further details.

**Figure 5: GHG emissions savings of German rapeseed FAME – comparison of N2O field emissions (5-year average) and fossil fuel comparator**

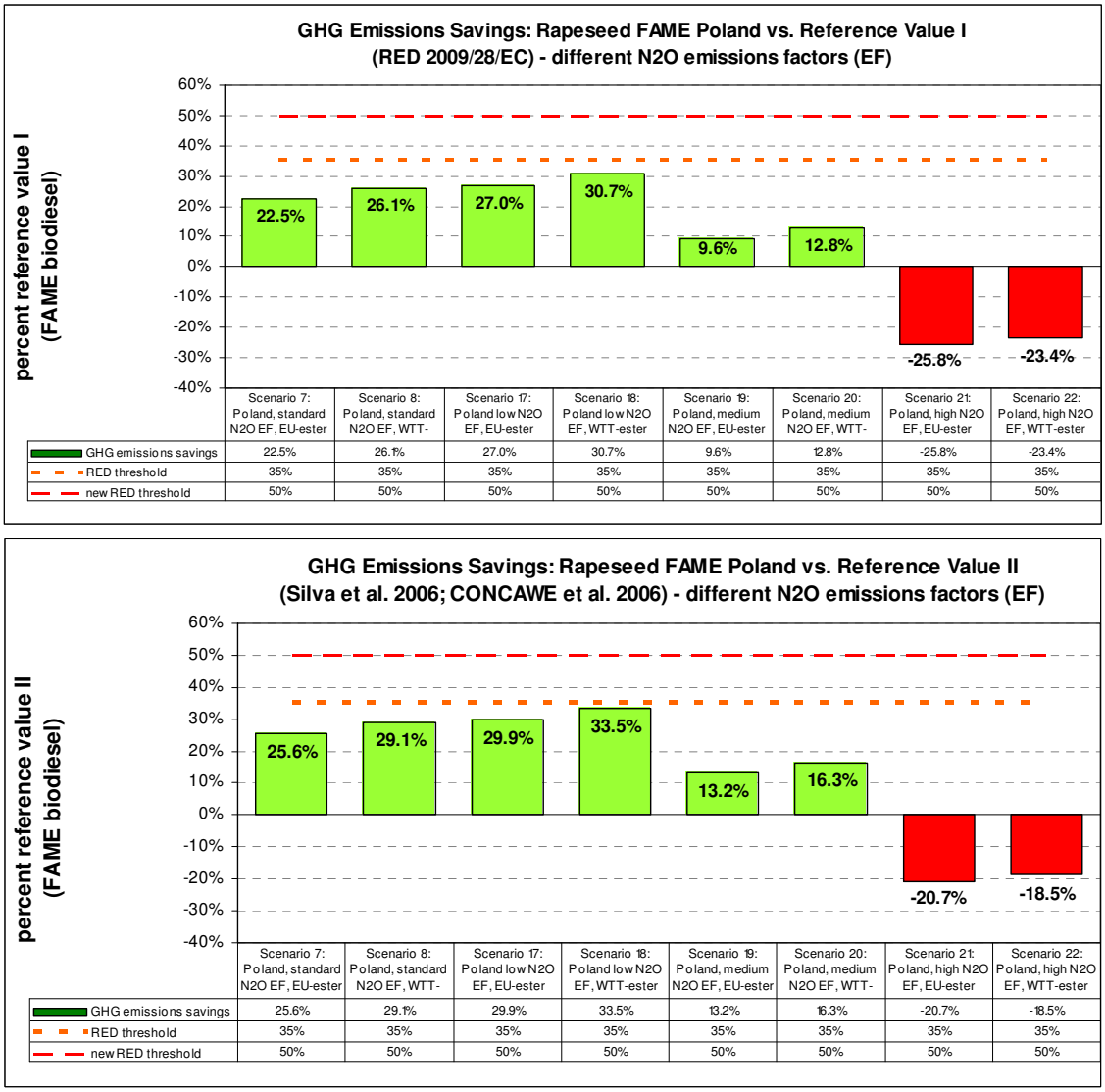



In the case of Polish and Romanian rapeseed the results also show broad variability. However, none of our scenarios result in GHG emissions saving above the 35% threshold. Instead, some results indicate the possibility of negative GHG emissions savings meaning that under very unfavourable conditions (e.g. very high N2O field emissions) rapeseed biofuels may cause even more GHG emissions than fossil diesel, and depart significantly from current official GHG emission estimates claimed by the European Commission.

For Poland (see table A-5 and figure 6), we calculate a best case GHG emissions saving value of 33.5% by assuming 80% of the standard N2O emissions factor proposed by the IPCC (2006), esterification values according WTT (Pehnelt and Vietze 2013) and a fossil fuel comparator as suggested by Silva et al. (2006) and CONCAWE et al. (2006). The worst case scenario is calculated with the maximum N2O field emissions as suggested by IPCC (2006),

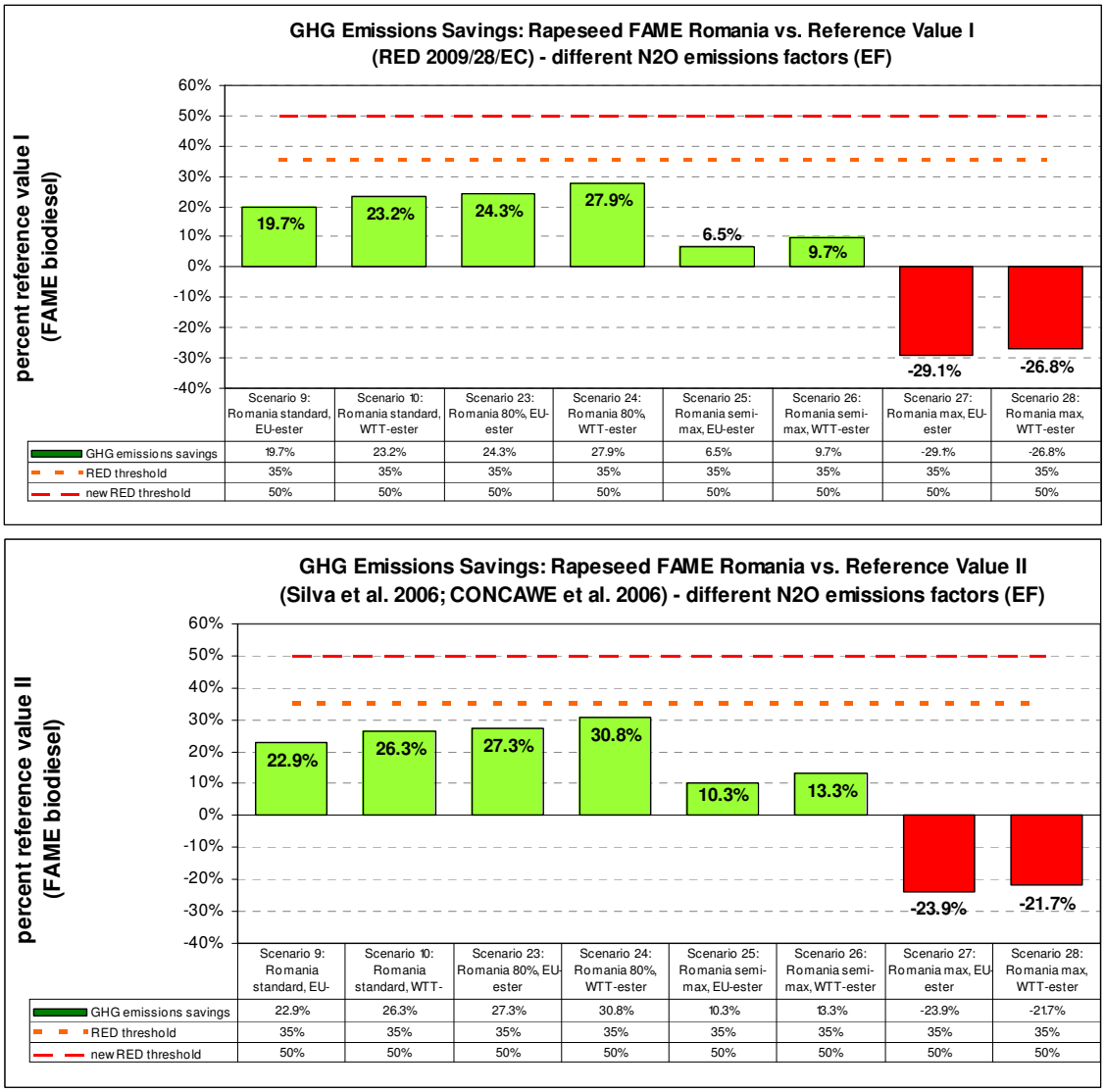
and EU (2009) esterification technology. By comparing this value with emission from fossil fuel according RED, we obtain a GHG emissions saving value of -25.8%.

**Figure 6: GHG emissions savings of Polish rapeseed FAME – comparison of N2O field emissions (5-year average) and fossil fuel comparator**




As displayed in table A-6 and figure 7, in case of Romanian rapeseed biodiesel our best case scenario result in an GHG emissions saving value of 30.8% while in the worst case we obtain a value of -29.1%.

**Figure 7: GHG emissions savings of Romanian rapeseed FAME – comparison of N2O field emissions (5-year average) and fossil fuel comparator**




In sum, all scenarios of rapeseed biodiesel production from both Poland and Romania – even when relying on rather favourable assumptions regarding the subsequent production steps – indicate a rather poor GHG emissions performance of rapeseed biodiesel. It is hardly imaginable that improvements in the production process will lead to a fulfilment of the advanced RED requirements in the near future.

### *A Note on Indirect Land-Use Change*

During the last couple of years, the issue of indirect land-use change (ILUC) has attracted much attention and has become one of the most prominent sources of uncertainty for biofuel production and regulation.

Theoretically, the phenomenon of indirect land-use change cannot be dismissed. Any activity in the context of tradable goods that is associated with land-use may create indirect effects on

land-use elsewhere. Biofuel production is prone to this phenomenon. By trend, the ecobalance of biofuels is affected negatively if ILUC is taken into account. Though, estimating the concrete mode of action, scale and scope of certain activities with respect to indirect effects on land-use on a global scale is very ambitious and cannot be done with a sufficient degree of certainty on the basis of existing methods. Using such 'guestimates' as a basis for the regulation of markets or single products comes along with a high risk – both with respect to the correct policies and incentives and within the framework of (international) trade and competition law. Because of these uncertainties regarding the reasons and effects of indirect land use change it is not possible to calculate realistic scenarios. Hence, just as in Pehnelt and Vietze (2012, 2013) we do not consider this problem explicitly in this paper.

However, since ILUC is one of the most prominent issues in the whole biofuel discussion, it cannot be foreclosed that ILUC-factors will make it into the regulation scheme. This creates an additional risk for European biofuel producers.

## 4. Conclusion and Policy Implications

The assessment of the sustainability of rapeseed biodiesel heavily depends on the very production conditions and assumptions regarding the N2O field emissions. As a matter of fact, not every liter of rapeseed biodiesel produced in the EU is 'sustainable' in the sense of RED. Therefore, the use of standard values (e.g. default values) in order to categorize rapeseed biodiesel – or any other biofuel – as sustainable or not is not justifiable.[10]

Our results can be interpreted as a claim for a comprehensive analysis and proof of the GHG emissions of every single production step. Therefore, a clear cut certification using the actual inventory data of the supply chain seems to be the only way to sufficiently assess the sustainability of certain biofuel fractions.

Given the results presented above, it is inevitable to use the most efficient sources for primary products, including cost efficient imports of raw material or intermediate products with a superior GHG emissions performance. Biodiesel using base materials originating from rather unproductive plantations (e.g. low yields per hectare) are very unlikely to fulfill even moderate sustainability criteria (e.g. 35% threshold) – not to mention the advanced requirements that will come into force in 2017/2018.

Existing potentials for efficiency improvements on every single step of the supply chain should be consequently utilized. The most significant potentials for such efficiency improvements with respect to the GHG emissions performance of rapeseed biodiesel are in the production and application of fertilizers, the yields and the esterification process. The overall GHG emissions

[10] Note: The introduction of general 'penalizing factors' (e.g. 1.4) to calculate default values may create incentives to prove the GHG emissions of the whole production chain but cannot be justified from a scientific point of view.

of the refinery process and transportation are already rather negligible and the potentials for further emissions reductions very modest.

From a regulatory perspective, incentives to enhance the efficiency and GHG performance of biodiesel production are appropriate whereas fixed quota (e.g. limiting the share of energy from first generation biofuels to 5 percent of the final energy consumption as suggested in a recent proposal by the EC) may not contribute to an enhancement of the overall efficiency of biofuel production.

There are significant annual and field specific fluctuations of the output in the field and the subsequent GHG emissions of the according fraction of biodiesel. As a matter of fact, a physical separation of single fractions is not practicable. Therefore, biofuel-specific emissions trading system with (intertemporally) tradable certificates seem to be a pragmatic policy option to – on the one hand – assure the sustainability of biofuel production and – on the other hand – to provide a certain extent of investment security and reliability to biofuel producers. Biofuel producers may be committed to prove that their output of the last three years on average fulfills the sustainability criteria. Within such a regulatory framework biofuel producers may compensate the gap between the GHG emissions savings of their output and the GHG emissions saving threshold in years with inferior efficiency (e.g. low yields per hectare) with a better than required GHG emissions performance of their output in subsequent years (e.g. higher yields per hectare).

So far, the EU's biofuel policy is not stringent and reliable especially given the upcoming negotiations regarding an amendment of RED. This causes a high uncertainty for all stakeholders. Consequently, the EU's biofuel policy has been heavily criticized by all sorts of stakeholders. Currently, there is no investment security for producers. That is why further growth of the European market for first generation biofuels is rather questionable under the current conditions, regulations and uncertainties.

The current ILUC-discussion and uncertainties about N2O emissions factors are the most important risk factors for producers and regulators.[11] The existing scientific basis for concrete ILUC-factors is not sufficient. Probably, field specific N2O analyses are necessary, but maybe not practicable and expensive.

[11] Note: The current food vs. energy discussion creates another political uncertainty because the issue is highly emotional and already has a remarkable impact on the public perception of biofuel production. However, without analyzing this issue explicitly in this paper, the whole argumentation is somehow exaggerated and partially misleading.

## References

Aarhus United (2004), Aarhus United - Energirapport (English: Aarhus United - Energy report), Aarhus: Aarhus United.

Aarhus United (2005a), Aarhus United - Miljørapport (English: Aarhus United – Environmental report), Aarhus: Aarhus United.

Aarhus United (2005b), Aarhus United - Energirapport (English: Aarhus United - Energy report), Aarhus: Aarhus United.

Akiyama, H., X. Yan, K. YAGI (2010), Evaluation of effectiveness of enhanced-efficiency fertilizers as mitigation options for N2O and NO emissions from agricultural soils: meta-analysis, *Global Change Biology* 16: 1837–1846.

Baquero, G., B. Esteban, J.-R. Riba, A. Rius, and R. Puig (2011), An evaluation of the life cycle cost of rapeseed oil as a straight vegetable oil fuel to replace petroleum diesel in agriculture, *Biomass and Bioenergy* 35: 3687-3697.

Baquero, G., B. Esteban, R. Puig, J.-R. Riba, and A. Rius (2013), Environmental life cycle assessment of rapeseed straight vegetable oil as self-supply agricultural biofuel, *Renewable Energy* 50: 142-149.

BioGrace (2012), Harmonised calculations of biofuel greenhouse gas emissions in Europe, BioGrace_GHG_calculations_-_version_4b_-_Public.xls Utrecht, The Netherlands et al.: BioGrace.

Bouwman, A.F., L.J.M. Boumans, and N.H. Batjes (2002), Modeling global annual N2O and NO emissions from fertilized fields, *Global Biogeochemical Cycles* 16(4): 28/1–28/9.

Brentrup, F., and C. Pallière (2008), *GHG emissions and energy efficiency in European nitrogen fertilizer production and use*, Proceedings 639, York, UK: International Fertilizer Society.

Brünning, F. (2012), Personal communication with Frank Brühning, spokesman of Verband der Deutschen Biokraftstoffindustrie e.V., Berlin.

Brankatschk, G. (2012), Personal communication with Gerhard Brankatschk, consultant of OVID – Verband der ölsaatenverarbeitenden Industrie in Deutschland e. V., Berlin.

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

Crutzen, P.J., A.R. Mosier, K.A. Smith, and W. Winiwarter (2007), N2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels, *Atmospheric Chemistry and Physics Discussions* 7: 11191-11205.

Crutzen, P.J., A.R. Mosier, K.A. Smith, and W. Winiwarter (2008), N2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels, *Atmospheric Chemistry and Physics* 8(2): 389-395.

Dalgaard, T. (2007), Personal communication with R. Dalgaard, co-author of the LCAfood database, Department of Development and Planning, Aalborg University and Danish

Institute of Agricultural Science. Denmark, In: Schmidt, J.H. (2007), Life assessment of rapeseed oil and palm oil. Ph.D. thesis, Part 3: Life cycle inventory of rapeseed oil and palm oil, Diss. Department of Development and Planning, Aalborg University.

Dalgaard, T., N. Halberg, and J.R. Porter (2001), A model for fossil energy use in Danish agriculture used to compare organic and conventional farming, *Agriculture, Ecosystems and Environment* 87: 51-65.

Dalgaard, R., N. Halberg, I. S. Kristensen, and I. Larsen (2006), Modelling representative and coherent farm types based on accountancy data for use in environmental assessments, *Agriculture, Ecosystems and Environment* 117: 223-237.

Dansk Landbrug (2004), Kornafregningsaftalen (English: Agreement on payment of cereals), Copenhagen: Dansk Landbrug.

Dansk Landbrugsrådgivning (2005a), Dyrkningsvejledning, Vinterraps (English: Cultivation guideline, winter rapeseed), Aarhus: Dansk Landbrugsrådgivning.

Dansk Landbrugsrådgivning (2005b), Dyrkningsvejledning, Vårraps (English: Cultivation guideline, spring rapeseed), Aarhus: Dansk Landbrugsrådgivning.

Davidson, E.A. (2009), The contribution of manure and fertilizer nitrogen to atmospheric nitrous oxide since 1860, *Nature Geoscience* 2: 659-662.

de Vries, S.C., G.W.J. van de Ven, M.K. van Ittersum, and K.E. Giller (2010), Resource use efficiency and environmental performance of nine major biofuel crops, processed by first-generation conversion techniques, *Biomass and Bioenergy* 34: 588-601.

Energistyrelsen (1995), Teknologidata for el- og varmeproduktionsanlæg (English: Data on technology of electricity- and heat cogeneration), Copenhagen: Energistyrelsen.

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

Falk (2012), Routenplaner (English: route planner), http://www.falk.de (Accessed October 2012).

FAOSTAT (2012), Production Crops, Rapeseed, http://faostat3.fao.org/home/index.html#DOWNLOAD (Accessed October 2012).

Firrisa, M.T. (2011), Energy Efficiency for Rapeseed Biofuel Production in Different Agro-Ecological Systems, Master thesis, Faculty of Geo-Information Science and Earth Observation, University of Twente, Enschede, The Netherlands.

Foley, J.A., N. Ramankutty, K.A. Brauman, E.S. Cassidy, J.S. Gerber, M.Johnston, N.D. Mueller, C. O'Connell, D.K. Ray, P.C. West, C. Balzer, E.M. Bennett, S.R. Carpenter, J. Hill, C. Monfreda, S. Polasky, J. Rockström, J. Sheehan, S. Siebert, D. Tilman, and D.P.M. Zaks (2011), Solutions for a cultivated planet, *Nature* 478: 337-342.

GM, LBST, BP, ExxonMobil, Shell, and TotalFinaElf (2002), Well-to-Wheel Analysis of Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems – A European Study, Ottobrunn, Germany: Ludwig-Bölkow-Systemtechnik GmbH.

Haberl, H., C. Körner, C. Lauk, U. Schmid-Staiger, V. Smetacek,E.D. Schulze, R. Thauer, P. Weiland, and K. Wilson (2012), The availability and sustainability of biomass as an energy source, In: Leopoldina (Ed.), *Bioenergy: Chances and Limits*, Halle (Saale): German National Academy of Sciences, 9-42.

Halleux, H., S. Lassaux, R. Renzoni, and A. Germain (2008), Comparative Life Cycle Assessment of Two Biofuels, Ethanol from Sugar Beet and Rapeseed Methyl Ester, *International Journal of Life Cycle Assessment*13 (3): 184-190.

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

Institut für Energie- und Umweltforschung Heidelberg GmbH (IFEU) (2011), Plant Oil GHG Calculator (rapeseed, sunflower, soy), 11 Plant_oil GHG Calculator IFEU_version1.xls, Heidelberg, Germany: IFEU.

IPCC (2006), IPCC Guidelines for National Greenhouse Gas Inventories, Volume 4, Chapter 11, N2O emissions from managed soils, and CO2 emissions from lime and urea application, Hayama, Japan: Institute for Global Environmental Strategies.

IPCC (2011), IPCC Expert Meeting on HWP, Wetlands and Soil $N_2O$, Meeting Report of the IPCC Expert Meeting on HWP, Wetlands and Soil $N_2O$, Geneva, Switzerland, 19-21 October, 2010, Hayama, Japan: Institute for Global Environmental Strategies.

Jacobsen, B.H., C.G. Sørensen, and J.F. Hansen (2002), Håndtering af husdyrgødning – en teknisk-økonomisk systemanalyse (English: Handling of animal manure in Denmark - a technical and economical system analysis), Rapport nr. 138, Copenhagen: Fødevareøkonomisk Institut.

Jensen, E.B., K. Jørgensen, C. Haldrup, K.A. Nielsen, B. Christensen, M. Wegge, T. Serup, F. Udesen, and J.J. Høy (2005), Budgetkalkuler 2006, for de enkelte produktionsgrene, (English: Budget estimates 2006, for single production lines), Aarhus: Dansk Landbrugsrådgivning.

Jenssen, T.K., and G. Kongshaug (2003), *Energy consumption and greenhouse gas emissions in fertilizer production*, Proceedings 509, York, UK: International Fertilizer Society.

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

Korning, J. (2006), Personal communication with J. Korning, quality manager, AarhusKarlshamn Denmark, Aarhus, In: Schmidt, J.H. (2007), Life assessment of rapeseed oil and palm oil. Ph.D. thesis, Part 3: Life cycle inventory of rapeseed oil and palm oil, Diss. Department of Development and Planning, Aalborg University.

Kronborg, L. (2006), Personal Communication with L. Kronborg, quality engineer, AarhusKarlshamn Denmark, Aarhus, In: Schmidt, J.H. (2007), Life assessment of rapeseed oil and palm oil. Ph.D. thesis, Part 3: Life cycle inventory of rapeseed oil and palm oil, Diss. Department of Development and Planning, Aalborg University.

Landwirtschaftskammer Nordrhein-Westfalen (LNW) (2012), Stickstoffdüngung im Raps (English: Nitrogen fertilizer in rapeseed), http://www.landwirtschaftskammer.de/landwirtschaft/ackerbau/raps/n-duengung-pdf.pdf (Accessed October 2012).

Lehuger, S., B. Gabrielle, P. Laville, M. Lamboni, B. Loubet, and P. Cellier (2011), Predicting and mitigating the net greenhouse gas emissions of crop rotations in Western Europe, *Agricultural and Forest Meteorology* 151: 1654-1671.

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

Mosier, A, C. Kroeze, C. Nevison, O. Oenema, S. Seitzinger, and O. van Cleemput (1998), Closing the global N2O budget; nitrous oxide emissions through the agricultural nitrogen cycle, *Nutrient Cycles in Agroecosystems* 52: 225-248.

Nemecek, T., A. Heil, O. Huguenin, S. Meier, S. Erzinger, S. Blaser, D. Dux, and A. Zimmermann (2003), Life Cycle Inventories of Agricultural Production Systems, Data v1.01, Final report ecoinvent 2000 No. 15, Dübendorf, Switzerland: FAL Reckenholz, FAT Tänikon, Swiss Centre for Life Cycle Inventories.

Nmin-NRW (2012), Düngeempfehlung (English: Fertilizer recommendations), http://www.nmin.de/nminnrw/DuengeStartAction.do?duengeStart=0 (Accessed October 2012).

Oil World (2005), Oil World Annual 2005, www.oilworld.biz (accessed Dezember 2005).

Pehnelt, G., and C. Vietze (2012), Uncertainties about the GHG Emissions Saving of Rapeseed Biodiesel, *Jena Economic Research Paper* 2012/39: 1-34.

Pehnelt, G., and C. Vietze (2013), Recalculating GHG emissions saving of palm oil biodiesel, *Environment, Development and Sustainability* 15(2): 429-479.

PortWorld Distances (2012), Distance Calculation, http://www.portworld.com/map (Accessed October 2012).

Raiffeisen (2012), Ackermanager – Raps/Ölfrüchte – Düngung (English: plantation manager – rapeseed/oilcrops – fertilizers), http://www.raiffeisen.com/pflanzen/ackermanager/raps_duengung_html (Accessed October 2012).

Rathke, G.-W., and W. Diepenbrock (2006), Energy balance of winter oilseed rape (Brassica napus L.) cropping as related to nitrogen supply and preceding crop, *European Journal of Agronomy* 24: 35-44.

Rathke, G.-W., O. Christen, and W. Diepenbrock (2005), Effects of nitrogen source and rate on productivity and quality of winter oilseed rape (Brassica napus L.) grown in different crop rotations, *Field Crops Research* 94: 103-113.

Rathke, G.-W., T. Behrens, and W. Diepenbrock (2006), Integrated nitrogen management strategies to improve seed yield, oil content and nitrogen efficiency of winter oilseed rape (Brassica napus L.): A review, *Agriculture, Ecosystems and Environment* 117, 80-108.

Reay, D.S., E.A. Davidson, K.A. Smith, P. Smith, J.M. Melillo, F. Dentener, and P.J. Crutzen (2012), Global agriculture and nitrous oxide emissions, *Nature Climate Change* 2: 410-416.

Reijnders, L., and M.A.J. Huijbregts (2008), Biogenic greenhouse gas emissions linked to the life cycles of biodiesel derived from European rapeseed and Brazilian soybeans, *Journal of Cleaner Production* 16: 1943-1948.

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

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

Schulze, E.D., P. Ciais, S. Luyssaert, M. Schrumpf, I.A. Janssens, B. Thiruchittampalam, J. Theloke, M. Saurat, S. Bringezu, J. Lelieveld, A. Lohila, C. Rebmann, M. Jung, D. Bastviken, G. Abril, G. Grassi, A. Leip, A. Freibauer, W. Kutsch, A. Don, J. Nieschulze, A. Börner, J.H. Gash, and A.J. Dolman (2010), The European carbon balance, Part 4: integration of carbon and other trace-gas fluxes, *Global Change Biology* 16(5): 1451-1469.

Smith, K.A., A.R. Mosier, P.J. Crutzen, and W. Winiwarter (2012), The role of N2O derived from crop based biofuels, and from agriculture in general, in Earth's climate, *Philosophical Transactions of the Royal Society B: Biological Sciences* 367: 1169-1174.

Thamsiriroj, T., and J.D. Murphy (2009), Is it better to import palm oil from Thailand to produce biodiesel in Ireland than to produce biodiesel from indigenous Irish rape seed?, *Applied Energy* 86: 595-604.

Thamsiriroj, T., and J.D. Murphy (2010), Can Rape Seed Biodiesel Meet the European Union Sustainability Criteria for Biofuels?, *Energy Fuels* 24: 1720-1730.

Wuebbles, D.J. (2009), Nitrous Oxide: No Laughing Matter, *Science* 326(5949): 56-57.

# Appendix

## Table A-1: Scenario 2 – German average, Esterification WTT

| Plantation | value | unit | source |
|---|---|---|---|
| ***output*** | | | |
| yield rape seed (RS) (fresh matter) | 3823.5 | kg RS / ha / year | German-average 2006-2010: FAOSTAT 2012 |
| moisture content in rape seed | 9.0 | per cent of RS | Schmidt 2007, Dansk Landbrug 2004 |
| straw removed from field | 678.4 | kg straw / ha / year | ratio of straw production (150% of dry matter RS yield): Biograce 2012; ratio of straw removed from field (13% of produced straw): Schmidt 2007 |
| ***input*** | | | |
| seed - rape seed (normed) | 9.0 | kg seeds / ha / year | Schmidt 2007, Dansk Landbrugsrådgivning 2005a, Nemecek et al. 2003 |
| N-fertiliser | 163.0 | kg N / ha / year | Raiffeisen 2012 (average); N-credit for crop rotation: Schmidt 2007, Jacobsen et al. 2002 |
| P2O5-fertiliser | 85.0 | kg P2O5 / ha / year | Raiffeisen 2012 (average) |
| K2O-fertiliser | 200.0 | kg K2O / ha / year | Raiffeisen 2012 (average) |
| CaO-fertiliser | 0 | kg CaO / ha / year | |
| Pesticides | 2.35 | kg ai / ha / year | de Vries et al. 2010, Halleux 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 |
| ***Emission factors N2O-field emissions*** | | | |
| EF for direct N2O field emissions | 1.00 | per cent N2O_N / kg N additions from N-fertilisers and crop residues | IPCC 2006, fraction of all added N that is lost directly as N2O per kg N applied as N-fertilizer and crop residues |
| EF for NH3&NOx volatilization | 1.00 | per cent N2O_N / kg N deposited as NH3 or NOx (10% of N from synthetic N-fertiliser) | IPCC 2006, fraction of synthetic fertiliser N that volatilises as NH3 and NOx is expected as 10% N-mass volatilised as NH3&Nox per kg of N applied as synthetic N-fertilizer (IPCC 2006) |
| EF for Nitrate leaching and runoff | 0.75 | per cent N2O_N / kg N leached and runoff as nitrate (30% of N from N-fertilizers and crop residues) | IPCC 2006, fraction of all added N that is lost through leaching and runoff as nitrate is expected as 30% N-mass leached as nitrate per kg of N applied as N-fertilizer and crop residues (IPCC 2006) |
| **GHG emissions after plantation** | **813.49** | **g CO2eq per kg RS** | Note: 190 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 (alloc.)** | **1227.82** | **g CO2eq per kg RefRSO** | |
| **GHG emissions of plantation (alloc.)** | **34.11** | **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 |
| ***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* | *0.622* | | |
| **GHG emissions after Oil Mill** | **1387.90** | **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 (alloc.)** | **183.66** | **g CO2eq per kg RefRSO** | |
| **GHG emissions of Oil Mill (alloc.)** | **5.10** | **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** | **1439.65** | **g CO2eq per kg RefRSO** | Note: The inventory date do not include deodorisation. 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 (alloc.)** | **28.18** | **g CO2eq per kg RefRSO** | |
| **GHG emissions of Refinery (alloc.)** | **0.78** | **g CO2eq per MJ RefRSO** | |

| Transport (to Hamburg) | value | unit | source |
|---|---|---|---|
| ***Transport (overland)*** | | | |
| average distance mill/refinery/port | 350 | km | Distance Niederdorla (geographic center Germany) - Port Hamburg, Germany: Falk 2012 |
| vehicle used transporting RefPO | Truck for Diesel | | Schmidt 2007 |
| used fuel for vehicle | Diesel | | Schmidt 2007 |
| **GHG emissions after Transport** | **1471.09** | **g CO2eq per kg RefRSO** | |
| **GHG emissions of Transport (alloc.)** | **31.44** | **g CO2eq per kg RefRSO** | |
| **GHG emissions of Transport (alloc.)** | **0.87** | **g CO2eq per MJ RefRSO** | |

| | | |
|---|---|---|
| **Total GHG emissions RefPO** | **1471.09** | **g CO2eq per kg RefRSO** |
| | **40.86** | **g CO2eq per MJ RefRSO** |
| **GHG emission savings compared to fossil comparator (electricity production)** | **55.1%** | 91 gCO2eq/MJ<br>RED 2009/28/EC |

**t.b.c**

## Table A-1: Scenario 2 (continued)

| Esterification WTT | value | unit | source |
|---|---|---|---|
| ***output*** | | | |
| produced FAME | 964.35 | t FAME / 1000 t RefRSO / year | Pehnelt and Vietze 2013 (according to WTT Appendix 1 (v3)) |
| Glycerine | 101.26 | t Glyc. / 1000 t RefRSO / year | Pehnelt and Vietze 2013 (according to WTT Appendix 1 (v3)) |
| ***input*** | | | |
| processed RefRSO | 1000.00 | t RefRSO / year | Pehnelt and Vietze 2013 (according to WTT Appendix 1 (v3)) |
| Methanol | 106.36 | t Meth. / 1000 t RefRSO / year | Pehnelt and Vietze 2013 (according to WTT Appendix 1 (v3)) |
| Phosphoric acid (H3PO4) | 1.79 | t H3PO4 / 1000 t RefRSO / year | Pehnelt and Vietze 2013 (according to WTT Appendix 1 (v3)) |
| Hydrochloric acid (HCl) | 19.73 | t HCl / 1000 t RefRSO / year | Pehnelt and Vietze 2013 (according to WTT Appendix 1 (v3)) |
| Sodium carbonate (Na2CO3) | 2.44 | t Na2CO3 / 1000 t RefRSO / year | Pehnelt and Vietze 2013 (according to WTT Appendix 1 (v3)) |
| Sodium Hydroxide (NaOH) | 6.64 | t NaOH / 1000 t RefRSO / year | Pehnelt and Vietze 2013 (according to WTT Appendix 1 (v3)) |
| ***Energy consumption*** | | | |
| Natural gas | 825102 | kWh / 1000 t RefRSO / year | Pehnelt and Vietze 2013 (according to WTT Appendix 1 (v3)) |
| Electricity (external) | 71748 | kWh / 1000 t RefRSO / year | Pehnelt and Vietze 2013 (according to WTT Appendix 1 (v3)) |
| Electricity mix | EU | | Pehnelt and Vietze 2013 (according to WTT Appendix 1 (v3)) |
| *Allocation factor after by-products* | *0.957* | | |

| | | |
|---|---|---|
| **CO2 emissions after Esterification** | **1930.29** | **g CO2eq per kg FAME** |
| **CO2 emissions of Esterification (ac.)** | **470.74** | **g CO2eq per kg FAME** |
| **CO2 emissions of Esterification (ac.)** | **12.65** | **g CO2eq per MJ FAME** |

| | | |
|---|---|---|
| **Total CO2 emissions FAME** | **1930.29** | **g CO2eq per kg FAME** |
| | **51.89** | **g CO2eq per MJ FAME** |
| **GHG emission savings compared to fossil comparator I (fuel diesel)** | **38.1%** | 83.8 g CO2eq/MJ<br>RED 2009/28/EC |
| **GHG emission savings compared to fossil comparator II (fuel diesel)** | **40.6%** | 87.3 g CO2eq/MJ<br>Silva et al. 2006; CONCAWE et al. 2006 |

## Table A-2: Scenario 7 and 8 – Polish average, Esterification EU (2009) and WTT

| Plantation | value | unit | source |
|---|---|---|---|
| ***output*** | | | |
| yield rape seed (RS) (fresh matter) | 2767.0 | kg RS / ha / year | Polish-average 2006-2010: FAOSTAT 2012 |
| moisture content in rape seed | 9.0 | per cent of RS | Schmidt 2007, Dansk Landbrug 2004 |
| straw removed from field | 491.0 | kg straw / ha / year | ratio of straw production (150% of dry matter RS yield): Biograce 2012; ratio of straw removed from field (13% of produced straw): Schmidt 2007 |
| ***input*** | | | |
| seed - rape seed (normed) | 9.0 | kg seeds / ha / year | Schmidt 2007, Dansk Landbrugsrådgivning 2005a, Nemecek et al. 2003 |
| N-fertiliser | 156.0 | kg N / ha / year | Firrisa 2011 (average); N-credit for crop rotation: Schmidt 2007, Jacobsen et al. 2002 |
| P2O5-fertiliser | 157.0 | kg P2O5 / ha / year | Firrisa 2011 (average); standardization: Schmidt 2007 |
| K2O-fertiliser | 132.0 | kg K2O / ha / year | Firrisa 2011 (average); standardization: Schmidt 2007 |
| CaO-fertiliser | 0 | kg CaO / ha / year | |
| Pesticides | 2.35 | kg ai / ha / year | de Vries et al. 2010, Halleux 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 |
| ***Emission factors N2O-field emissions*** | | | |
| EF for direct N2O field emissions | 1.00 | per cent N2O_N / kg N additions from N-fertilisers and crop residues | IPCC 2006, fraction of all added N that is lost directly as N2O per kg N applied as N-fertilizer and crop residues |
| EF for NH3&NOx volatilization | 1.00 | per cent N2O_N / kg N deposited as NH3 or NOx (10% of N from synthetic N-fertiliser) | IPCC 2006, fraction of synthetic fertiliser N that volatilises as NH3 and NOx is expected as 10% N-mass volatilised as NH3&Nox per kg of N applied as synthetic N-fertilizer (IPCC 2006) |
| EF for Nitrate leaching and runoff | 0.75 | per cent N2O_N / kg N leached and runoff as nitrate (30% of N from N-fertilizers and crop residues) | IPCC 2006, fraction of all added N that is lost through leaching and runoff as nitrate is expected as 30% N-mass leached as nitrate per kg of N applied as N-fertilizer and crop residues (IPCC 2006) |

| | | | |
|---|---|---|---|
| **GHG emissions after plantation** | **1051.08** | **g CO2eq per kg RS** | Note: 183 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** | **1586.42** | **g CO2eq per kg RefRSO** | |
| **GHG emissions of plantation** | **44.07** | **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*** | | | |
| 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 |
| ***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* | *0.622* | | |

| | | | |
|---|---|---|---|
| **GHG emissions after Oil Mill** | **1746.51** | **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** | **189.75** | **g CO2eq per kg RefRSO** | |
| **GHG emissions of Oil Mill** | **5.27** | **g CO2eq per MJ RefRSO** | |

**t.b.c.**

## Table A-2: Scenario 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** | **1804.35** | **g CO2eq per kg RefRSO** | Note: The inventory date do not include deodorisation. 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 | 300 | km | Distance Ozorków (geographic center of Poland) - Port Gdansk, Poland: Falk 2012 |
| vehicle used transporting RefPO | Truck for Diesel | | Schmidt 2007 |
| used fuel for vehicle | Diesel | | Schmidt 2007 |
| ***Transport (ship)*** | | | |
| average distance Spain-Europe | 1500 | km | Distance Port Gdansk, Poland - Port Rotterdam, The Netherlands: PortWorld Distances 2012 |
| vehicle used transporting RefPO | Tanker 50kt | | Schmidt 2007 |
| used fuel for vehicle | HFO | | Schmidt 2007 |

| | | |
|---|---|---|
| **GHG emissions after Transport** | **1847.35** | **g CO2eq per kg RefRSO** |
| **GHG emissions of Transport** | **43.01** | **g CO2eq per kg RefRSO** |
| **GHG emissions of Transport** | **1.19** | **g CO2eq per MJ RefRSO** |

| | | |
|---|---|---|
| **Total GHG emissions RefPO** | **1847.35** | **g CO2eq per kg RefRSO** |
| | **51.32** | **g CO2eq per MJ RefRSO** |
| **GHG emission savings compared to fossil comparator (electricity production)** | **43.6%** | 91 gCO2eq/MJ<br>RED 2009/28/EC |

| Esterification EU | 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)) |
| Phosphoric 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** | **2414.62** | **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** | **2414.62** | **g CO2eq per kg FAME** |
| | **64.91** | **g CO2eq per MJ FAME** |
| **GHG emission savings compared to fossil comparator I (fuel diesel)** | **22.5%** | 83.8 g CO2eq/MJ<br>RED 2009/28/EC |
| **GHG emission savings compared to fossil comparator II (fuel diesel)** | **25.6%** | 87.3 g CO2eq/MJ<br>Silva et al. 2006; CONCAWE et al. 2006 |

| Esterification WTT | value | unit | source |
|---|---|---|---|
| ***output*** | | | |
| produced FAME | 964.35 | t FAME / 1000 t RefRSO / year | Pehnelt and Vietze 2013 (according to WTT Appendix 1 (v3)) |
| Glycerine | 101.26 | t Glyc. / 1000 t RefRSO / year | Pehnelt and Vietze 2013 (according to WTT Appendix 1 (v3)) |
| ***input*** | | | |
| processed RefRSO | 1000.00 | t RefRSO / year | Pehnelt and Vietze 2013 (according to WTT Appendix 1 (v3)) |
| Methanol | 106.36 | t Meth. / 1000 t RefRSO / year | Pehnelt and Vietze 2013 (according to WTT Appendix 1 (v3)) |
| Phosphoric acid (H3PO4) | 1.79 | t H3PO4 / 1000 t RefRSO / year | Pehnelt and Vietze 2013 (according to WTT Appendix 1 (v3)) |
| Hydrochloric acid (HCl) | 19.73 | t HCl / 1000 t RefRSO / year | Pehnelt and Vietze 2013 (according to WTT Appendix 1 (v3)) |
| Sodium carbonate (Na2CO3) | 2.44 | t Na2CO3 / 1000 t RefRSO / year | Pehnelt and Vietze 2013 (according to WTT Appendix 1 (v3)) |
| Sodium Hydroxide (NaOH) | 6.64 | t NaOH / 1000 t RefRSO / year | Pehnelt and Vietze 2013 (according to WTT Appendix 1 (v3)) |
| ***Energy consumption*** | | | |
| Natural gas | 825102 | kWh / 1000 t RefRSO / year | Pehnelt and Vietze 2013 (according to WTT Appendix 1 (v3)) |
| Electricity (external) | 71748 | kWh / 1000 t RefRSO / year | Pehnelt and Vietze 2013 (according to WTT Appendix 1 (v3)) |
| Electricity mix | EU | | Pehnelt and Vietze 2013 (according to WTT Appendix 1 (v3)) |
| *Allocation factor after by-products* | *0.957* | | |

| | | |
|---|---|---|
| **CO2 emissions after Esterification** | **2303.60** | **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** | **2303.60** | **g CO2eq per kg FAME** |
| | **61.92** | **g CO2eq per MJ FAME** |
| **GHG emission savings compared to fossil comparator I (fuel diesel)** | **26.1%** | 83.8 g CO2eq/MJ<br>RED 2009/28/EC |
| **GHG emission savings compared to fossil comparator II (fuel diesel)** | **29.1%** | 87.3 g CO2eq/MJ<br>Silva et al. 2006; CONCAWE et al. 2006 |

## Table A-3: Scenario 9 and 10 – Romanian average, Esterification EU (2009) and WTT

| Plantation | value | unit | source |
|---|---|---|---|
| ***output*** | | | |
| yield rape seed (RS) (fresh matter) | 1586.5 | kg RS / ha / year | Romaian-average 2006-2010: FAOSTAT 2012 |
| moisture content in rape seed | 0.0 | per cent of RS | Baquero et al. 2011, 2013 |
| straw removed from field | 309.4 | kg straw / ha / year | ratio of straw production (150% of dry matter RS yield): Biograce 2012; ratio of straw removed from field (13% of produced straw): Schmidt 2007 |
| ***input*** | | | |
| seed - rape seed (normed) | 6.1 | kg seeds / ha / year | Baquero et al. 2011, 2013, standardization: Nemecek et al. 2003 |
| N-fertiliser | 88.0 | kg N / ha / year | Baquero et al. 2011, 2013 (average); N-credit for crop rotation: Schmidt 2007, Jacobsen et al. 2002 |
| P2O5-fertiliser | 125.9 | kg P2O5 / ha / year | Baquero et al. 2011, 2013; standardization: Schmidt 2007 |
| K2O-fertiliser | 55.5 | kg K2O / ha / year | Baquero et al. 2011, 2013; standardization: Schmidt 2007 |
| CaO-fertiliser | 0 | kg CaO / ha / year | |
| Pesticides | 2.35 | kg ai / ha / year | de Vries et al. 2010, Halleux et al. 2008 |
| Diesel (all activities and transport) | 70.0 | l / ha / year | Baquero et al. 2011 |
| electricity (storage, drying of RS) | 0 | kWh / t RS | Baquero et al. 2011, 2013 |
| ***Emission factors N2O-field emissions*** | | | |
| EF for direct N2O field emissions | 1.00 | per cent N2O_N / kg N additions from N-fertilisers and crop residues | IPCC 2006, fraction of all added N that is lost directly as N2O per kg N applied as N-fertilizer and crop residues |
| EF for NH3&NOx volatilization | 1.00 | per cent N2O_N / kg N deposited as NH3 or NOx (10% of N from synthetic N-fertiliser) | IPCC 2006, fraction of synthetic fertiliser N that volatilises as NH3 and NOx is expected as 10% N-mass volatilised as NH3&Nox per kg of N applied as synthetic N-fertilizer (IPCC 2006) |
| EF for Nitrate leaching and runoff | 0.75 | per cent N2O_N / kg N leached and runoff as nitrate (30% of N from N-fertilizers and crop residues) | IPCC 2006, fraction of all added N that is lost through leaching and runoff as nitrate is expected as 30% N-mass leached as nitrate per kg of N applied as N-fertilizer and crop residues (IPCC 2006) |

| | | | |
|---|---|---|---|
| **GHG emissions after plantation** | **1060.08** | **g CO2eq per kg RS** | Note: 115 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. The drying stage is usually unnecessary thanks to climate conditions in south Europe (Baquero et al. 2011). Thus, no drying is considered in the study. |
| **GHG emissions of plantation** | **1600.00** | **g CO2eq per kg RefRSO** | |
| **GHG emissions of plantation** | **44.44** | **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*** | | | |
| 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 |
| ***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* | *0.622* | | |

| | | | |
|---|---|---|---|
| **GHG emissions after Oil Mill** | **1760.10** | **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** | **189.99** | **g CO2eq per kg RefRSO** | |
| **GHG emissions of Oil Mill** | **5.28** | **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** | **1818.16** | **g CO2eq per kg RefRSO** | Note: The inventory date do not include deodorisation. 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 | 615 | km | Distance Dealu Frumos (geographic center Romania) - Port Constanța, Romania: Falk 2012 |
| vehicle used transporting RefPO | Truck for Diesel | | Schmidt 2007 |
| used fuel for vehicle | Diesel | | Schmidt 2007 |
| ***Transport (ship)*** | | | |
| average distance Spain-Europe | 6150 | km | Distance Port Constanța, Romania - Port Rotterdam, Netherlands: PortWorld Distances 2012 |
| vehicle used transporting RefPO | Tanker 50kt | | Schmidt 2007 |
| used fuel for vehicle | HFO | | Schmidt 2007 |

| | | |
|---|---|---|
| **GHG emissions after Transport** | **1939.24** | **g CO2eq per kg RefRSO** |
| **GHG emissions of Transport** | **121.07** | **g CO2eq per kg RefRSO** |
| **GHG emissions of Transport** | **3.36** | **g CO2eq per MJ RefRSO** |

| | | |
|---|---|---|
| **Total GHG emissions RefPO** | **1939.24** | **g CO2eq per kg RefRSO** |
| | **53.87** | **g CO2eq per MJ RefRSO** |
| **GHG emission savings compared to fossil comparator (electricity production)** | **40.8%** | 91 gCO2eq/MJ<br>RED 2009/28/EC |

**t.b.c.**

## Table A-3: Scenario 9 and 10 (continued)

| Esterification EU | 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)) |
| Phosphoric 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** | **2503.55** | **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** | **2503.55** | **g CO2eq per kg FAME** |
| | **67.30** | **g CO2eq per MJ FAME** |
| **GHG emission savings compared to fossil comparator I (fuel diesel)** | **19.7%** | 83.8 g CO2eq/MJ<br>RED 2009/28/EC |
| **GHG emission savings compared to fossil comparator II (fuel diesel)** | **22.9%** | 87.3 g CO2eq/MJ<br>Silva et al. 2006; CONCAWE et al. 2006 |

| Esterification WTT | value | unit | source |
|---|---|---|---|
| ***output*** | | | |
| produced FAME | 964.35 | t FAME / 1000 t RefRSO / year | Pehnelt and Vietze 2013 (according to WTT Appendix 1 (v3)) |
| Glycerine | 101.26 | t Glyc. / 1000 t RefRSO / year | Pehnelt and Vietze 2013 (according to WTT Appendix 1 (v3)) |
| ***input*** | | | |
| processed RefRSO | 1000.00 | t RefRSO / year | Pehnelt and Vietze 2013 (according to WTT Appendix 1 (v3)) |
| Methanol | 106.36 | t Meth. / 1000 t RefRSO / year | Pehnelt and Vietze 2013 (according to WTT Appendix 1 (v3)) |
| Phosphoric acid (H3PO4) | 1.79 | t H3PO4 / 1000 t RefRSO / year | Pehnelt and Vietze 2013 (according to WTT Appendix 1 (v3)) |
| Hydrochloric acid (HCl) | 19.73 | t HCl / 1000 t RefRSO / year | Pehnelt and Vietze 2013 (according to WTT Appendix 1 (v3)) |
| Sodium carbonate (Na2CO3) | 2.44 | t Na2CO3 / 1000 t RefRSO / year | Pehnelt and Vietze 2013 (according to WTT Appendix 1 (v3)) |
| Sodium Hydroxide (NaOH) | 6.64 | t NaOH / 1000 t RefRSO / year | Pehnelt and Vietze 2013 (according to WTT Appendix 1 (v3)) |
| ***Energy consumption*** | | | |
| Natural gas | 825102 | kWh / 1000 t RefRSO / year | Pehnelt and Vietze 2013 (according to WTT Appendix 1 (v3)) |
| Electricity (external) | 71748 | kWh / 1000 t RefRSO / year | Pehnelt and Vietze 2013 (according to WTT Appendix 1 (v3)) |
| Electricity mix | EU | | Pehnelt and Vietze 2013 (according to WTT Appendix 1 (v3)) |
| *Allocation factor after by-products* | *0.957* | | |

| | | |
|---|---|---|
| **CO2 emissions after Esterification** | **2394.76** | **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** | **2394.76** | **g CO2eq per kg FAME** |
| | **64.38** | **g CO2eq per MJ FAME** |
| **GHG emission savings compared to fossil comparator I (fuel diesel)** | **23.2%** | 83.8 g CO2eq/MJ<br>RED 2009/28/EC |
| **GHG emission savings compared to fossil comparator II (fuel diesel)** | **26.3%** | 87.3 g CO2eq/MJ<br>Silva et al. 2006; CONCAWE et al. 2006 |

## Table A-4: GHG emissions of German rapeseed FAME – comparison of N2O-field emissions (5-year average)

| Scenario No | GHG emissions (g CO2eq per MJ rape FAME) | | | | | | GHG emissions savings rape FAME | |
|---|---|---|---|---|---|---|---|---|
| | Plantation | Oil mill | Refinery | Transport | Esterification | total FAME | % reference value I (RED) | % reference value II |
| Scenario 1: Germany, standard N2O EF, EU-ester | 31.95 | 4.78 | 0.73 | 0.82 | 16.84 | 55.12 | **34.2%** | **36.9%** |
| Scenario 2: Germany, standard N2O EF, WTT-ester | 32.75 | 4.90 | 0.75 | 0.84 | 12.65 | 51.89 | **38.1%** | **40.6%** |
| Scenario 11: Germany low N2O EF, EU-ester | 28.95 | 4.73 | 0.73 | 0.82 | 16.84 | 52.07 | **37.9%** | **40.4%** |
| Scenario 12: Germany low N2O EF, WTT-ester | 29.67 | 4.85 | 0.75 | 0.84 | 12.65 | 48.76 | **41.8%** | **44.1%** |
| Scenario 11: Germany, medium N2O EF, EU-ester | 40.64 | 4.93 | 0.73 | 0.82 | 16.84 | 63.96 | **23.7%** | **26.7%** |
| Scenario 12: Germany, medium N2O EF, WTT-ester | 41.66 | 5.05 | 0.75 | 0.84 | 12.65 | 60.95 | **27.3%** | **30.2%** |
| Scenario 13: Germany, high N2O EF, EU-ester | 64.36 | 5.33 | 0.73 | 0.82 | 16.84 | 88.08 | **-5.1%** | **-0.9%** |
| Scenario 14: Germany, high N2O EF, WTT-ester | 65.97 | 5.46 | 0.75 | 0.84 | 12.65 | 85.68 | **-2.2%** | **1.9%** |

## Table A-5: GHG emissions of Polish rapeseed FAME – comparison of N2O-field emissions (5-year average)

| Scenario No | GHG emissions (g CO2eq per MJ rape FAME) | | | | | | GHG emissions savings rape FAME | |
|---|---|---|---|---|---|---|---|---|
| | Plantation | Oil mill | Refinery | Transport | Esterification | total FAME | % reference value I (RED) | % reference value II |
| Scenario 7: Poland standard, EU-ester | 41.28 | 4.94 | 0.73 | 1.12 | 16.84 | 64.91 | 22.5% | 25.6% |
| Scenario 8: Poland standard, WTT-ester | 42.31 | 5.06 | 0.75 | 1.15 | 12.65 | 61.92 | 26.1% | 29.1% |
| Scenario 17: Poland 80%, EU-ester | 37.60 | 4.87 | 0.73 | 1.12 | 16.84 | 61.17 | 27.0% | 29.9% |
| Scenario 18: Poland 80%, WTT-ester | 38.54 | 5.00 | 0.75 | 1.15 | 12.65 | 58.09 | 30.7% | 33.5% |
| Scenario 19: Poland semi-max, EU-ester | 51.98 | 5.12 | 0.73 | 1.12 | 16.84 | 75.79 | 9.6% | 13.2% |
| Scenario 20: Poland semi-max, WTT-ester | 53.28 | 5.25 | 0.75 | 1.15 | 12.65 | 73.08 | 12.8% | 16.3% |
| Scenario 21: Poland max, EU-ester | 81.08 | 5.61 | 0.73 | 1.12 | 16.84 | 105.39 | -25.8% | -20.7% |
| Scenario 22: Poland max, WTT-ester | 83.11 | 5.75 | 0.75 | 1.15 | 12.65 | 103.41 | -23.4% | -18.5% |

## Table A-6: GHG emissions of Romanian rapeseed FAME – comparison of N2O-field emissions (5-year average)

| Scenario No | GHG emissions (g CO2eq per MJ rape FAME) | | | | | | GHG emissions savings rape FAME | |
|---|---|---|---|---|---|---|---|---|
| | Plantation | Oil mill | Refinery | Transport | Esterification | total FAME | % reference value I (RED) | % reference value II |
| Scenario 9: Romania standard, EU-ester | 41.63 | 4.94 | 0.73 | 3.15 | 16.84 | 67.30 | 19.7% | 22.9% |
| Scenario 10: Romania standard, WTT-ester | 42.67 | 5.07 | 0.75 | 3.23 | 12.65 | 64.38 | 23.2% | 26.3% |
| Scenario 23: Romania 80%, EU-ester | 37.87 | 4.88 | 0.73 | 3.15 | 16.84 | 63.47 | 24.3% | 27.3% |
| Scenario 24: Romania 80%, WTT-ester | 38.82 | 5.00 | 0.75 | 3.23 | 12.65 | 60.45 | 27.9% | 30.8% |
| Scenario 25: Romania semi-max, EU-ester | 52.47 | 5.13 | 0.73 | 3.15 | 16.84 | 78.33 | 6.5% | 10.3% |
| Scenario 26: Romania semi-max, WTT-ester | 53.79 | 5.26 | 0.75 | 3.23 | 12.65 | 75.68 | 9.7% | 13.3% |
| Scenario 27: Romania max, EU-ester | 81.83 | 5.63 | 0.73 | 3.15 | 16.84 | 108.19 | -29.1% | -23.9% |
| Scenario 28: Romania max, WTT-ester | 83.88 | 5.77 | 0.75 | 3.23 | 12.65 | 106.29 | -26.8% | -21.7% |

## Table A-7: Background data

| BACKGROUND DATA<br>parameter:<br>unit: | | GHG emission coefficient | | | | | | | | Fossil energy input | | LHV<br>MJ/kg<br>(at 0% water) | Fuel efficiency<br>MJ/t.km | Transport exhaust gas emissions | | Source |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $gCO_2$/kg | $gCH_4$/kg | $gN_2O$/kg | $gCO_{2\text{-}eq}$/kg | $gCO_2$/MJ | $gCH_4$/MJ | $gN_2O$/MJ | $gCO_{2\text{-}eq}$/MJ | $MJ_{fossil}$/kg | $MJ_{fossil}$/MJ | | | $gCH_4$/t.km | $gN_2O$/t.km | |
| *Global Warming Potentials (GWP's)* | | | | | | | | | | | | | | | | |
| $CO_2$ | 1 | | | | | | | | | | | | | | | RED Annex V.C.5 |
| $CH_4$ | 25 | | | | | | | | | | | | | | | RED Annex V.C.5 |
| $N_2O$ | 298 | | | | | | | | | | | | | | | RED Annex V.C.5 |
| *Agro inputs* | | | | | | | | | | | | | | | | |
| N-fertiliser (kg N) | | 2827.0 | 8.68 | 9.6418 | 5917.2 | | | | | 48.99 | | | | | | JEC E3-database (version 31-7-2008) |
| $P_2O_5$-fertiliser (kg $P_2O_5$) | | 964.9 | 1.33 | 0.0515 | 1013.5 | | | | | 15.23 | | | | | | JEC E3-database (version 31-7-2008) |
| $K_2O$-fertiliser (kg $K_2O$) | | 536.3 | 1.57 | 0.0123 | 579.2 | | | | | 9.68 | | | | | | JEC E3-database (version 31-7-2008) |
| CaO-fertiliser (kg CaO) | | 119.1 | 0.22 | 0.0183 | 130.0 | | | | | 1.97 | | | | | | JEC E3-database (version 31-7-2008) |
| Pesticides | | 9886.5 | 25.53 | 1.6814 | 11025.7 | | | | | 268.40 | | | | | | JEC E3-database (version 31-7-2008) |
| Seeds- rapeseed | | 412.1 | 0.91 | 1.0028 | 733.7 | | | | | 7.87 | | | | | | JEC E3-database (version 31-7-2008) |
| *Fuels- gasses* | | | | | | | | | | | | | | | | |
| Natural gas (4000 km, Russian NG quality) | | | | | | 61.58 | 0.1981 | 0.0002 | 66.59 | | 1.1281 | | | | | JEC E3-database (version 31-7-2008) |
| Natural gas (4000 km, EU Mix qualilty) | | | | | | 62.96 | 0.1981 | 0.0002 | 67.98 | | 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 | - | - | 87.64 | | 1.16 | 43.1 | | | | JEC E3-database (version 31-7-2008) |
| Gasoline | | | | | | | | | | | | 43.2 | | | | JEC E3-database (version 31-7-2008) |
| HFO | | | | | | 84.98 | - | - | 84.98 | | 1.088 | 40.5 | | | | JEC E3-database (version 31-7-2008) |
| HFO for maritime transport | | | | | | 87.20 | - | - | 87.20 | | 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 | 100.15 | | 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<br>parameter:<br>unit: | | GHG emission coefficient | | | | | | | | Fossil energy input | | LHV<br>MJ/kg<br>(at 0% water) | Fuel efficiency | Transport exhaust gas emissions | | Source |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $gCO_2$/kg | $gCH_4$/kg | $gN_2O$/kg | $gCO_{2\text{-eq}}$/kg | $gCO_2$/MJ | $gCH_4$/MJ | $gN_2O$/MJ | $gCO_{2\text{-eq}}$/MJ | $MJ_{fossil}$/kg | $MJ_{fossil}$/MJ | | MJ/t.km | $gCH_4$/t.km | $gN_2O$/t.km | |
| *Electricity* | | | | | | | | | | | | | | | | |
| Electricity EU mix MV | | | | | | 119.36 | 0.2911 | 0.0054 | 128.25 | | 2.6951 | | | | | JEC E3-database (version 31-7-2008) |
| Electricity EU mix LV | | | | | | 120.79 | 0.2946 | 0.0055 | 129.79 | | 2.7275 | | | | | JEC E3-database (version 31-7-2008) |
| *Conversion inputs* | | | | | | | | | | | | | | | | |
| n-Hexane | | | | | | 80.08 | 0.0146 | 0.0003 | 80.53 | | 0.3204 | 45.1 | | | | JEC E3-database (version 31-7-2008) |
| Phosphoric acid ($H_3PO_4$) | | 2776.0 | 8.93 | 0.1028 | 3029.80 | | | | | 28.57 | | | | | | JEC E3-database (version 31-7-2008) |
| Fuller's earth | | 197.0 | 0.04 | 0.0063 | 199.81 | | | | | 2.54 | | | | | | JEC E3-database (version 31-7-2008) |
| Hydrochloric acid (HCl) | | 717.4 | 1.13 | 0.0254 | 753.17 | | | | | 15.43 | | | | | | JEC E3-database (version 31-7-2008) |
| Sodium carbonate ($Na_2CO_3$) | | 1046.0 | 6.20 | 0.0055 | 1202.64 | | | | | 13.79 | | | | | | JEC E3-database (version 31-7-2008) |
| Sodium hydroxide (NaOH) | | 438.5 | 1.03 | 0.0240 | 471.40 | | | | | 10.22 | | | | | | JEC E3-database (version 31-7-2008) |
| Potassium hydroxide (KOH) | | 0.0 | 0.00 | 0.0000 | 0.00 | | | | | 0.00 | | | | | | |
| Hydrogen (for HVO) | | | | | | 80.87 | 0.2765 | 0.0003 | 87.87 | | 1.4835 | | | | | JEC E3-database (version 31-7-2008) |
| Pure CaO for processes | | 1013.0 | 0.65 | 0.0076 | 1031.49 | | | | | 4.60 | | | | | | JEC E3-database (version 31-7-2008) |
| Sulphuric acid ($H_2SO_4$) | | 193.9 | 0.55 | 0.0045 | 208.83 | | | | | 3.90 | | | | | | JEC E3-database (version 31-7-2008) |
| Ammonia | | 2478.0 | 7.84 | 0.0087 | 2676.53 | | | | | 44.39 | | | | | | JEC E3-database (version 31-7-2008) |
| Cycle-hexane | | 723.0 | 0.00 | 0.0000 | 723.00 | | | | | 53.10 | | | | | | JEC E3-database (version 31-7-2008) |
| Lubricants | | 947.0 | 0.00 | 0.0000 | 947.00 | | | | | 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 $N_2O$ emissions from NG boiler | | | | | | | 0.0028 | 0.0011 | 0.40 | | | | | | | JEC E3-database (version 31-7-2008) |
| $CH_4$ and $N_2O$ emissions from NG CHP | | | | | | | 0.0000 | 0.0000 | 0.00 | | | | | | | JEC E3-database (version 31-7-2008) |
| $CH_4$ and $N_2O$ emissions from Lignite CHP | | | | | | | 0.0023 | 0.0126 | 3.82 | | | | | | | JEC E3-database (version 31-7-2008) |
| $CH_4$ and $N_2O$ emissions from NG gas engine | | | | | | | 0.0533 | 0.0000 | 1.33 | | | | | | | JEC E3-database (version 31-7-2008) |

Source: Own compilation according to IFEU (2011)