FOOD & BIOBASED RESEARCH
WAGENINGEN UR

Sustainability aspects of biobased products: comparison of different crops and products from the vegetable oil platform

Meesters K.P.H., WUR Food & Biobased Research
Corré W.J., WUR Plant Research International
Conijn J.G., WUR Plant Research International
Patel M.K., Copernicus Institute
Bos H.L., WUR Food & Biobased Research

Report 1441

Sustainability aspects of biobased products: comparison of different crops and products from the vegetable oil platform

Meesters K.P.H., WUR Food & Biobased Research
Corré W.J., WUR Plant Research International
Conijn J.G., WUR Plant Research International
Patel M.K., Copernicus Institute
Bos H.L., WUR Food & Biobased Research

Report 1441

Colophon

Title	Sustainability of biobased products (Vegetable oil based products)
Author(s)	Meesters K.P.H., Corré W.J., Conijn J.G., Patel M.K., Bos H.L.
Number	Food & Biobased Research number
ISBN-number	978-94-6173-982-7
Date of publication	November 2012
Confidentiality	No
OPD code	OPD code
Approved by	R. van Ree

Wageningen UR Food & Biobased Research
P.O. Box 17
NL-6700 AA Wageningen
Tel: +31 (0)317 480 084
E-mail: info.fbr@wur.nl
Internet: www.wur.nl

Abstract

Currently large investments in the development of a biobased economy are made. The aim for a sustainable society is one of the driving forces behind this development. The most important feedstocks for the biobased economy are (a.) sugars (or carbohydrates) and (b.) vegetable oil.
a.) Last year a study on sugar based products was performed by Bos *et al.* (2011).
b.) The present study focusses on the production of vegetable oil based products. A limited number of aspacts of the sustainability of the full chain (from agriculture to product at the factory gate) was evaluated. Three different vegetable oils were taken into account: palm oil, soy oil and rapeseed oil. Also three different products made from vegetable oil were evaluated: biodiesel, polyol (a raw material for production of PU foams) and resin.
In the present study, sustainability of these products was evaluated through the following parameters:

- Non-Renewable Energy Usage (NREU) (GJ per ton of product)
- Greenhouse Gas (GHG) emissions (ton CO_2-equivalent per ton of product)
- Land use (ha/ton vegetable oil) and NREU and GHG emission avoided (GJ or ton CO_2-equivalent per hectare of land)

When producing vegetable oil from oil producing crops, protein rich side streams are produced (considerable amounts with soy and rapeseed oil and only small amounts with palm oil). During calculation of NREU and GHG emissions the assignment of agricultural inputs and emissions to oil and protein is inevitable.
Several methods for assignment may be used:

- System expansion
- Allocation (mass, energy or price based)

In the present study, system expansion was used. The results were compared to allocation methods based on mass, energy and price ratio.
Besides the protein rich co-product, oilseed crops also produce straw. In a fully developed biobased economy, it is expected that this co-product will also be used. Analysis with current practice (straw is left in the field) and with production of electricity from straw was performed.
Consequences of land use change (LUC), direct and indirect, were not taken into account.

Production of vegetable oil (system expansion)
Considering the exchangeability of the oils and the use of co-products, five cases were distinguished (see Figure 7):

1) Palm oil is used for biobased product; palm oil is marginal oil
2) Soy oil is used for biobased product; palm oil is marginal oil
3) Rapeseed oil is used for biobased product; palm oil is marginal oil
4) Rapeseed oil is grown for biobased product; palm oil is marginal oil
5) Rapeseed oil is used for biobased product; rapeseed oil is marginal oil

NREU, GHG emissions and land use for oil production are equal for the first three cases since they all involve increased production of palm oil. The production of rapeseed oil (case 4 and 5) causes a slightly higher NREU and land use but considerably higher GHG emission due to the high N fertilizer use during cultivation compared to palm oil (in case 5 this difference is a bit more pronounced than in case 4). The use of straw for energy has a positive effect on the NREU and GHG emissions of rapeseed oil production (case 4 and 5); rapeseed oil production even becomes a net energy producer. The NREU and GHG emissions from palm oil production (case 1, 2 and 3) get slightly higher when using straw for energy (see next paragraph). If production of electricity is included in the system expansion method, it should be realized that the production of electricity from straw is an efficient way to reduce NREU, but it is also an expensive way. Costs were not included as an impact factor in the analysis and therefore it must be kept in mid that the high costs for burning of straw for production of electricity might prevent introduction of the assumed scenario.

Comparison of system expansion with allocation methods

Allocation methods do not take exchange of oils and specific use of co-products into account but allocate part of the NREU, GHG emission or land use to the co-products and hence, these methods give different results for different crops. For palm oil (case 1), having a small proportion of co-products, the difference is small. For soy oil (case 2), the NREU and GHG emissions are higher if mass allocation is applied. For rapeseed oil the NREU and GHG emissions with application of mass allocation are higher than case 3 but lower than case 4 and 5. The NREU and GHG emissions and land use using energy or price allocation are clearly higher than using mass allocation in all cases.

If production of electricity from straw is assumed, the fundamental difference between system expansion and other accounting methods becomes evident. Using system expansion, the NREU of vegetable oil production (case 1, 2 and 3) increases slightly. Using mass allocation, the NREU of soy oil and rapeseed oil production becomes lower. System expansion assumes that even though the demand for soy or rapeseed oil is increased, the actual production of soy or rapeseed oil will decrease (as palm oil is grown instead where also some meal is produced). (Mass) allocation methods assume that soy or rapeseed is indeed produced and that the co-produced straw will result in lower NREU and GHG emission. This illustrates that allocation methods cannot take market shifts into account and therefore the use of system expansion, despite its uncertainties, is to be preferred.

Products from vegetable oils

All vegetable oil based product chains have lower NREU and GHG emissions than the fossil based reference.

NREU and GHG emission savings per ton of product decrease according to:

polyol > biodiesel > resin.

NREU and GHG emission savings per hectare decrease according to:

polyol > resin > biodiesel.
In case 1, 2 and 3, the results are equal for palm, soy and rapeseed oil based products.
In case 4 and 5, rapeseed oil based products have considerably lower GHG emission reduction.
Rapeseed oil based products (case 4 and 5) have slightly lower NREU reduction compared to case 1, 2 and 3 if current practice is assumed. If straw is used to produce electricity, the NREU reduction is higher for rapeseed oil based products. These differences are caused by differences occurring during oil production, during oil processing no differences between the three oils occur.
The resin has only a very low biobased content. Therefore the avoided NREU and GHG emissions per ton of product are very low. If NREU and GHG emissions are expressed per hectare, the difference is much smaller and the production of resin is better than production of biodiesel.
The reduction of NREU and GHG emissions of vegetable oil based products is comparable to sugar based products (reduction of NREU by approximately 300 GJ/ha and reduction of GHG emissions by approximately 20 ton/ha (assuming current practice)).

After this report was finished, data became available that made the additional calculation of the effects of the use of oil palm side products for the production of electricity possible. These data are presented in appendix B1. As can be expected, the use of side products for electricity production leads to a large decrease in the NREU and GHG emissions for the oil palm system, both become negative with the system expansion method (this counts for all data in case 1,2 and 3).

A comprehensive summary of this study is available in Dutch from the web-site www.groenegrondstoffen.nl.

Contents

1 Introduction

Currently large investments in the development of a biobased economy are made. The aim for a sustainable society is one of the driving forces behind this development. The term sustainability is ambiguous and often not without controversy. In this study, sustainability will be evaluated through the following parameters:

- Non-Renewable Energy Usage (NREU) (GJ per ton of product)
- Green House Gas (GHG) emissions (ton CO_2-equivalent per ton of product)
- Land use (NREU and GHG emissions avoided per hectare of land)

The most important feedstocks for the biobased economy are (a.) sugars (or carbohydrates) and (b.) vegetable oils.

a.) In 2010 a study on sugar based product chains was conducted (Bos *et al.*, 2011). From this study it was seen that the most efficient way to improve sustainability is through synthesis of products that are difficult to produce from crude oil. If synthesis from crude oil is difficult, a lot of energy is usually needed to produce the desired product with relatively low efficiency causing large emissions of greenhouse gasses per ton of product. The production of fossil counterparts was included for comparison.

b.) The present study will follow the same approach as the sugar study (Bos *et al.*, 2011), but it will focus on vegetable oil based products instead of sugar based products (Figure 2). Pure plant oil (PPO) will act as a central intermediate.

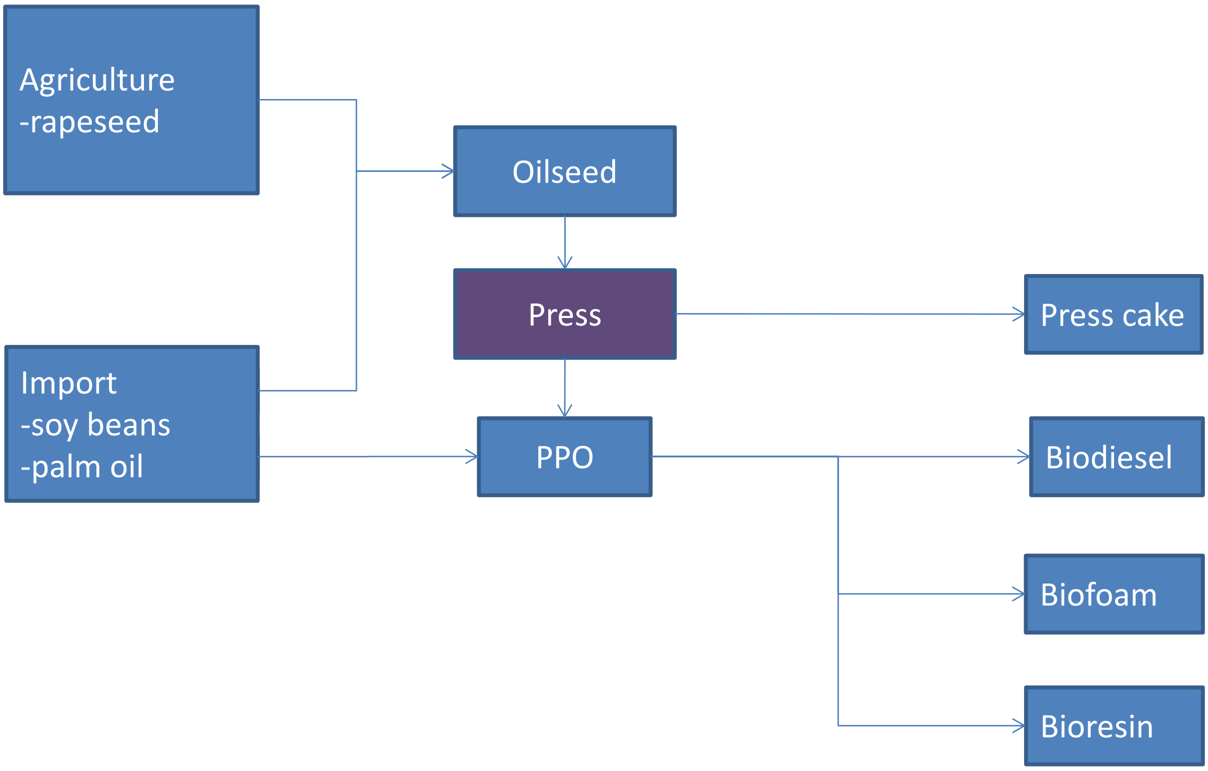


Figure 1, Vegetable oil (PPO) based product chains

In Figure 2, the vegetable oil based products and the respective reference products are shown.

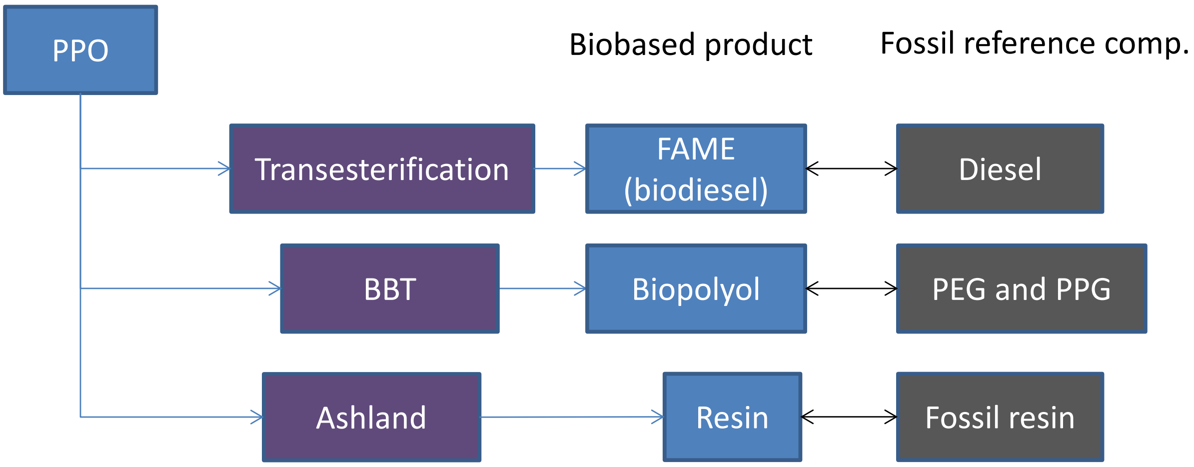


Figure 2, Biobased products based on pure vegetable oil (PPO) and fossil reference components

PPO	Pure Plant Oil
BBT	BioBased Technology: Manufacturer of soy oil based polyol
Ashland	Manufacturer of soy oil based resin
PEG	Poly Ethylene Glycol
PPG	Poly Propylene Glycol

Objective

The objective of this project is to assess the difference in sustainability between vegetable oil-based product chains and fossil reference chains with respect to NREU, GHG emission and land use.

Delineation

This study will focus on vegetable oil based product chains. The study includes agriculture and all conversion processes to deliver the product at the factory gate. The chains are compared with fossil reference chains. End of use waste treatment is not included in the analysis.

Meal or press cake is a major co-product from most oil chains. Taking co-products into account is needed to divide the emissions from agriculture, transport and oil extraction over the vegetable oil and the meal or press cake. Allocation methods are frequently used and allocation may be based on mass, energy or price ratio. Via system expansion, allocation can be prevented (this is the preferred option according to ISO 14044). Different methods might lead to quite different results. In this study system expansion with palm oil and wheat production are used as a default method. Results calculated with allocation methods will be presented and discussed to highlight the differences.

Approach

The NREU and GHG emissions of the total process chain from agriculture till final product were analyzed.

WUR-PRI provided agricultural data for the production of vegetable oil from different crops. A system expansion method was applied to deal with co-products.

The NREU and GHG emission data for manufacturing the final products were taken from 'Life Cycle Impact of Soybean Production and Soy Industrial Products' a publication by Omni Tech International (2010), as interpreted by WUR-FBR. The authors of this article have been so kind to provide additional data to correct for different starting points. Also the fossil reference chains were taken from this article.

Based on the agricultural data from WUR-PRI and the manufacturing data derived from Omni Tech International, the NREU and GHG emissions of the total production chain were derived. The NREU and GHG emission data were compared to the reference chain data of their fossil counterparts. It is assumed that the different plant oils can be interchanged on a one to one basis during manufacturing of the products. This does not hold for the production of polyols and resin from palm oil. As palm oil has hardly any double bonds, it cannot be used in these applications.

Tasks

- WUR-PRI provided agricultural data up to crude vegetable oil for different crops (Soy, Palm and Rapeseed).
- WUR-PRI conducted a system expansion with palm and wheat to account for the co-products and for comparison with other methods
- Omni Tech International provided additional data to correct for different starting points of their study
- WUR-FBR converted the data from Omni Tech International (2010) to comply with the starting points of the present study
- WUR-FBR derived NREU and GHG emission data for the manufacturing of products based on the data given in the article of Omni Tech International (2010)
- WUR-FBR connected the agricultural data of WUR-PRI with the manufacturing data of Omni Tech International (the agricultural data by Omni Tech International were discarded)
- WUR-FBR compared the NREU and GHG emission data of the vegetable oil based products with comparable products from fossil resources
- UU provided its expert opinion and facilities for database access

2 Starting points

The following starting points will be used in this study:

- System boundaries: Cradle to factory gate
- System expansion is used to account for the use of oil crop meal as animal feed in the production chain of vegetable oil
- System expansion is used to account for the production of electricity from straw in the fully developed biobased scenario
- Mass allocation was used in the analysis of the product chain from vegetable oil to vegetable oil based products
- Recently fixed CO_2 is **not** included as a negative CO_2 emission for the evaluation of vegetable oil from agriculture
- Recently fixed CO_2 is included as a negative CO_2 emission for the evaluation of products made from vegetable oil
- Embedded fossil energy is included in NREU values
- Nuclear energy (for production of electricity from the grid) is included in NREU values

These starting points are equal to the starting points of the sugar based products study by Bos *et al.*, 2011. One exception: in the sugar chain, system expansion was used supposing all co-products were converted to energy, use of protein rich co-products as animal feed was not considered.

Omni Tech International recently produced an LCA study on renewable products from soy bean oil (Omni Tech International, 2010). The starting points (system boundaries, accounting methods, etc.) of the Omni Tech International study are different from the starting points used in the present study.

Starting points of article by Omni Tech International (2010):

- System boundaries: Cradle to factory gate
- Allocation: allocation based on mass ratios unless stated otherwise
- Recently fixed CO_2 is included as a negative CO_2 emission
- Embedded fossil energy is **not** included as NREU

With the valuable assistance of the authors, the data of the Omni Tech International article (2010) could be recalculated to comply with the same starting points as this study.

3 Production of vegetable oil from different crops

3.1 Production of vegetable oil

Vegetable oil consists of tri-glycerides: three fatty acids that are connected to glycerine via ester bonds. The fatty acid composition is crop specific and determines the differences between the different vegetable oils. Vegetable oil is present in a large number of agricultural crops but only three major crops (rapeseed, palm and sunflower) are mainly grown for oil production with protein rich meal as a co-product. Together with soy bean, grown primarily for the meal, these crops provide over 85% of the world's vegetable oil production (see Table 1). Other oil producing crops are groundnut, cottonseed, coconut and olive and a large number of minor crops which have negligible shares in the total production. The total vegetable oil world production (130 Mt on average in the period 2005-2009, Table 1) was steadily increasing from 120 Mt in 2005 to 138 Mt in 2009 (FAOSTAT, 2011).

Palm produces two kinds of oil: the palm oil, circa 90%, extracted from the fruit and suitable for use comparable with rapeseed oil, sunflower oil and soy oil; and the palm kernel oil, extracted from the kernels, a lauric oil (with C_{12} saturated fatty acids), comparable with coconut oil (Schmidt & Weidema, 2008). As coconut needs at least seven years from planting to produce oil and is predominantly planted by small-holders, it is not likely to react to market demand as a marginal crop (Schmidt & Weidema, 2008). Palm oil and palm kernel oil are mostly used separately but since the two types of oil are produced in a fixed ratio in statistics 'palm oil' is considered the sum of palm oil and palm kernel oil. As the fatty acid composition of the different vegetable oils is different, one oil can be better suited for a certain application than others. However, for a number applications, e.g. cooking, the oils are exchangeable and increased demand for a certain oil will not directly lead to increase of its production but rather to an inc7rease of the production of the marginal oil crop, currently being oil palm (Schmidt & Weidema, 2008).

It is typical for the production of vegetable oil (and other agricultural products) that only a part of the harvestable biomass delivers the main product and other components result in co-products. These co-products can be divided in two types. Agricultural co-products result from the harvest, like wood from oil palm and straw from soy bean and rapeseed. They deliver no vegetable oil but can be used for other purposes. The perennial oil palm delivers wood at the end of its life cycle, usually circa 25 years after planting. The annual oil crops produce straw that can be used as stable bedding or animal feed but this straw is mostly left in the field. All agricultural co-products can be used to generate energy. The other type of co-products results from processing the main product; they remain when the oil is extracted. When seeds of the annual oil crops are extracted, the co-product is a protein rich meal, well suited for use in animal feed. In oil palm, the harvested 'fresh fruit bunches' are separated in kernels, pulp and 'empty fruit bunches'. When palm kernel oil is extracted, co-products are a protein rich meal, comparable with the meal of annual oilseed crops, and palm kernel shells. When palm oil is extracted from the pulp, the remaining biomass is separated into fibres and wastewater; the fibres are, together with the palm kernel shells, mostly used to generate energy for the palm oil mill and the wastewater is discharged, mostly after treatment. Sometimes wastewater is still discharged without proper treatment, causing large emissions of methane (Corley & Tinker, 2003). The empty fruit bunches are used as mulch or composted; the mulch and compost are used to fertilise the oil palm plantations. Flow charts of the three production chains studied are shown in Figure 3 till Figure 5.

Table 1, World vegetable oil production in the period 2005/2009 (from: FAOSTAT, 2011)

	Oil production in Mton yr^{-1}	% of world production
Palm oil	38.7	29.7
Palm kernel oil	5.1	3.9
Soy bean oil	35.8	27.5
Rapeseed oil	18.5	14.2
Sunflower oil	11.5	8.8
Groundnut oil	5.4	4.1
Cottonseed oil	4.9	3.8
Coconut oil	3.6	2.7
Olive oil	2.8	2.1
Maize oil	2.3	1.7
Sesame oil	0.9	0.7
Linseed oil	0.7	0.5
Safflower oil	0.1	0.1
Total[a]	130.3	100

[a]: Some minor vegetable oils (castor oil, jatropha oil) are not present in FAOSTAT ‘processed crops’ statistics.

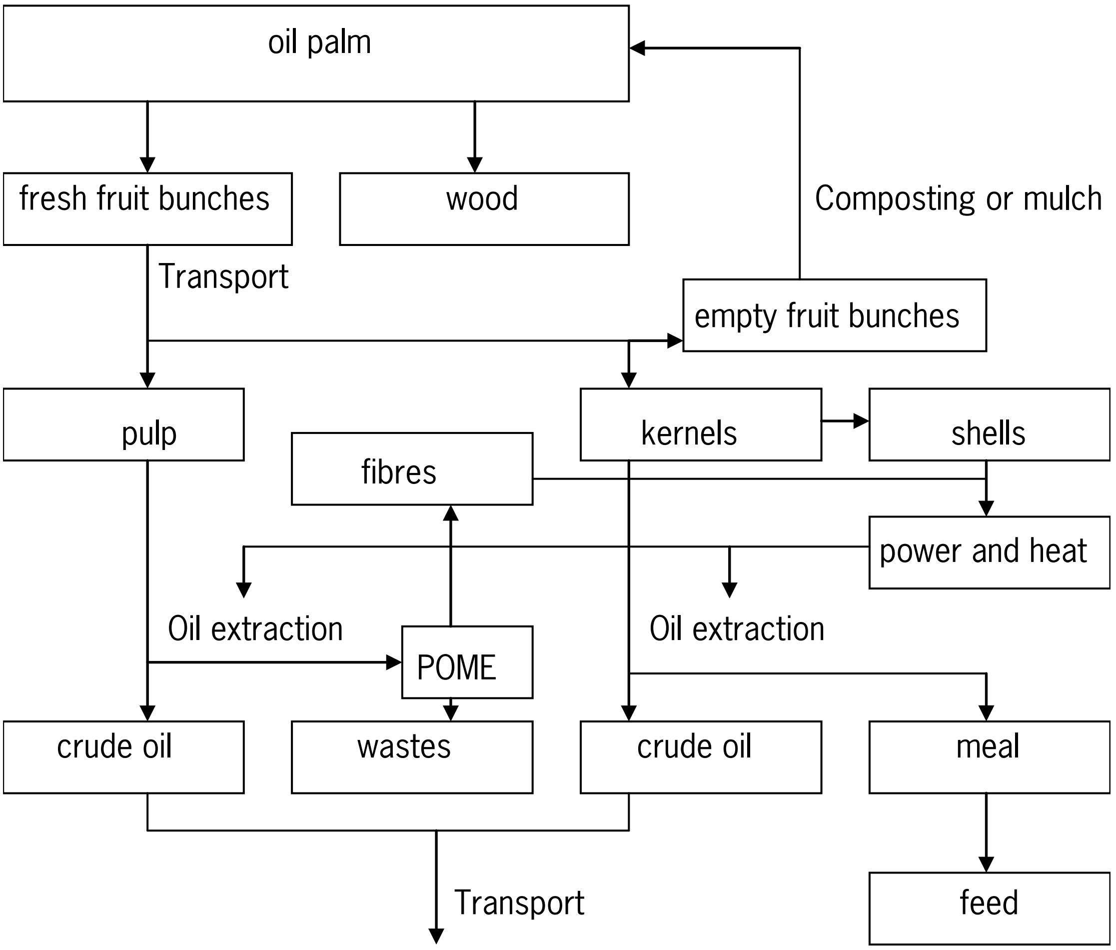


Figure 3, Flow chart for the production of vegetable oil from oil palm.

For this study, production of palm oil is assumed in South-East Asia, the region where 80% of the world's production is located. Fresh fruit bunches are harvested and transported over a short distance to be processed in small scale oil mills. The fruit bunches are separated into empty fruit bunches, which are mostly recycled in the oil palm plantations as mulch or compost, and pulp and kernels from which the oil is extracted. After pressing out the fibres the liquid remains of the pulp (POME: palm oil mill effluent) are sometimes still treated in open ponds but increasingly treated to prevent emission of methane. The kernel shells are mostly used for energy production by combustion, together with the fibres from the fruits, in a combined heat and power plant (CHP) to provide the palm oil mill with steam and power. The remains of the kernels after oil extraction are a protein rich meal (PKE: palm kernel expeller) which is usually used in animal feed. The crude vegetable oil is transported directly to Europe or to a larger scale installation for refining and after that the refined vegetable oil is transported to Europe. Circa twenty five years after planting the productivity of oil palms decreases and the trees grow too tall for proper harvesting of the fruit bunches and the crop needs replanting. The co-product wood (trunks) can be used for several purposes, like plywood and board, but is currently still mostly left in the field. Eventual produced energy is not used for oil extraction since according to current practice the combustion of fibres and shells can already deliver an energy surplus. A mass balance of the harvest is presented in Table 2.

Table 2, Mass balance of the average annual Malaysian oil palm yield (after Hansen *et al.*, 2012).

	kg ha^{-1} yr^{-1} (fresh)	% dry matter
Fresh fruit bunches	19,000	
Crude palm oil	3,850	
Crude palm kernel oil	460	
Palm kernel meal	510	
Residues	14,140	
Water addition	6,500	
Empty fruit bunches	4,230	34
Fibres	2,520	61
Shells	1,290	89
POME	12,540	4

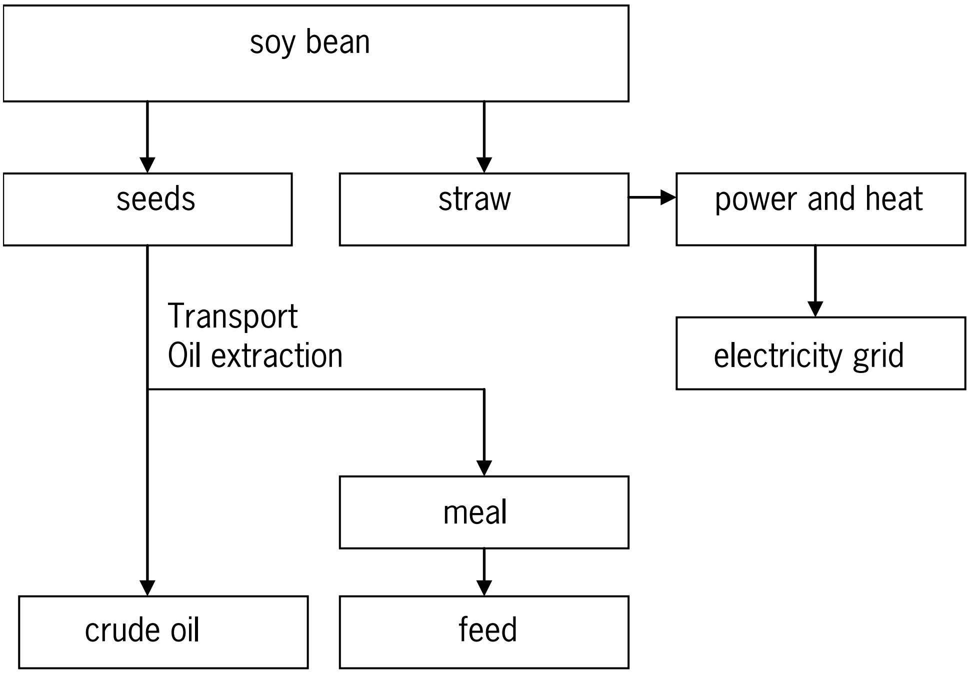


Figure 4, Flow chart for the production of vegetable oil from soy bean.

The cultivation of soy bean is assumed in Brazil, one of the world's most important exporting countries. Ripe seeds are harvested and stored and usually transported over a long distance to be processed in large scale installations. The straw is usually left in the field but could be used for the production of energy. Power could be delivered to the electricity grid, however, due to the availability of ample electricity from hydropower in Brazil this is currently not an economically feasible option. Soy beans contain circa 20% oil and the remains of the seeds, circa 80% of the weight, is the protein rich soy meal which is widely used in animal feed. Mostly soy beans are exported to Europe, but soy oil and soy meal are also exported separately.

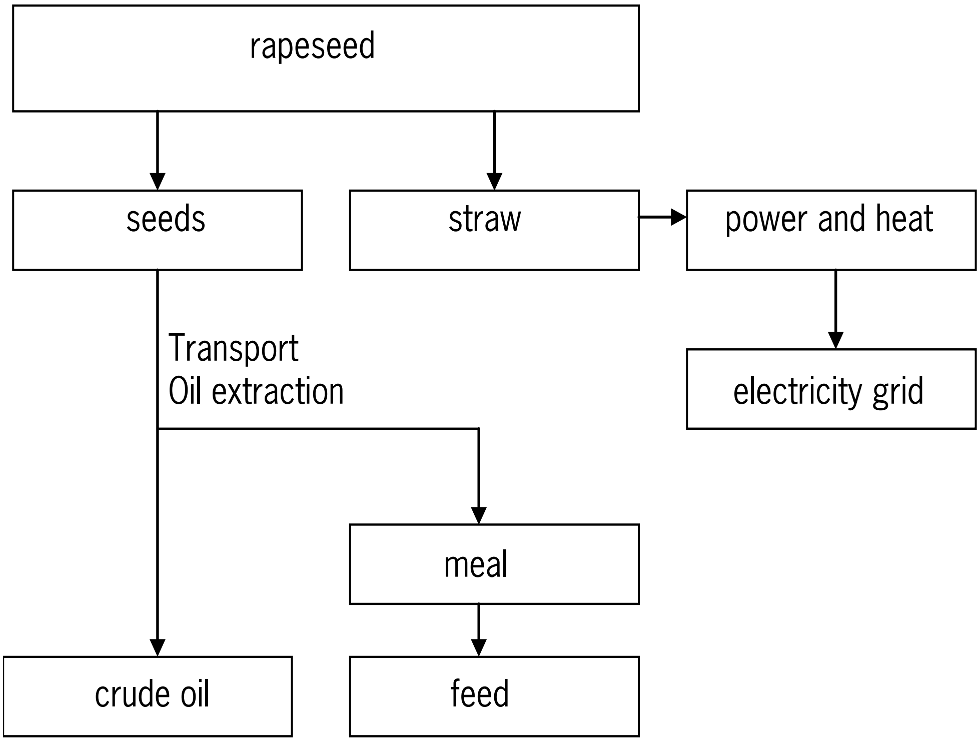


Figure 5, Flow chart for the production of vegetable oil from rapeseed.

The cultivation of rapeseed is assumed in Europe. Ripe seeds are harvested, eventually dried, and stored and transported to be processed in large scale installations. The straw is usually left in the field but could be used for the production of energy. Power can be delivered to the electricity grid but straw is not yet a common source of energy in Europe. Rape seed contains circa 40% oil and the remains of the seeds is the protein rich rapeseed meal which is used in animal feed.

3.2 Dealing with co-products

In vegetable oil production chains, only a part of the crop is processed to vegetable oil while co-products like straw and oilseed meal are used for other purposes, for instance as animal feed. Hence, also only a part of the energy use, GHG emissions and land use should be assigned to the main product and the other part should be assigned to the co-products. The methodology of assigning energy use and emissions to co-products can greatly influence the outcome of the study.

Performing this assignment, however, is a complex problem for which different methods exist. The most simple, commonly used method is allocation to different (co-)products by means of attribution on the basis of energy content, economic value or mass of the different (co-)products. An example is the use of attribution on the basis of energy content in the production of biofuels as prescribed in the EU 'Renewable Energy Directive' (RED; EC, 2009). However, according to ISO 14044 (ECS, 2005-a, ECS, 2005-b) allocation should be avoided by expanding the production system to include the additional functions related to the co-products whenever possible. And although system expansion for agricultural production can easily lead to complex system descriptions, it is principally always possible to use system expansion (Weidema, 2001). Following ISO, we aim at avoiding allocation by applying system expansion. In the case of system expansion the bio-based production system (e.g. vegetable oil from rapeseed) should be compared to a reference system not only producing the *main* product from a fossil source (i.e. mineral oil) but to an extended system, also producing a product comparable to the *co-product* of the biobased production system (see Figure 6). In this way the consequences of bringing a co-product to the market become visible. For example, since the rapeseed-vegetable oil chain yields rapeseed meal as a co-product, the system should be extended with a product that typically can be replaced by rapeseed meal. Since all oil crops have a protein rich meal as co-product and these oil crop meals strongly dominate the market for protein rich feed components, extending the production of one type of vegetable oil will affect the market for protein meals and therefore also the market for other oil crops. This will lead to interactions between the different oil crops as described in Section 3.3.

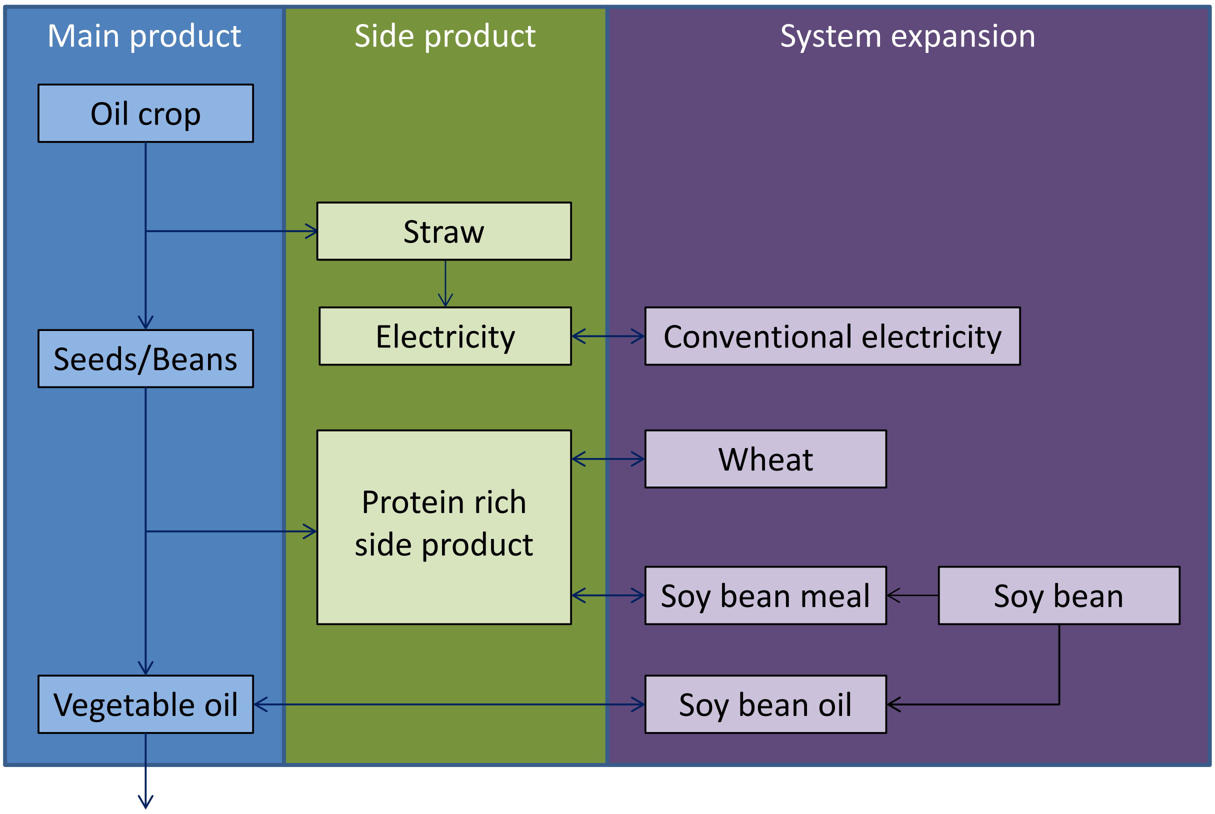


Figure 6, Assignment of NREU and GHG emissions to side products through system expansion

Other co-products are empty fruit bunches, kernel shells and wood from palm and straw from annual oilseed crops. The kernel shells and empty fruit bunches are recycled within the palm oil production system for the production of energy for the oil mill and for use as organic fertiliser (mulch or compost) in the palm plantations. Hence, increased or reduced production does not

affect other products and requires no system expansion. The energy production in the palm oil mills is not as efficient as possible, however, more efficient production would require selling the electricity surplus to the grid, which is not (yet) economically feasible. Palm wood can be used as timber or as firewood; however, due to a lack of data on production and use it is not possible to perform a system expansion with the use of wood. Straw is only partly used and mostly left in the field. Increased production is therefore not likely to affect the actual use of straw and a system expansion is not feasible (Weidema, 2001). On the other hand, straw can be used for the production of energy and will then replace fossil energy.
Regarding the feasible use of co-products two scenarios were made: ‘straw for energy’ where straw is combusted for the production of energy and ‘common practice’ where straw is left in the field. The scenarios are described in details in Section 3.4. However, it should be noted that the amount of soil organic matter will be different between these two scenarios and that the effect of this on net GHG emission calculation has not been taken into account in this study.

3.3 Interactions between crops in vegetable oil production

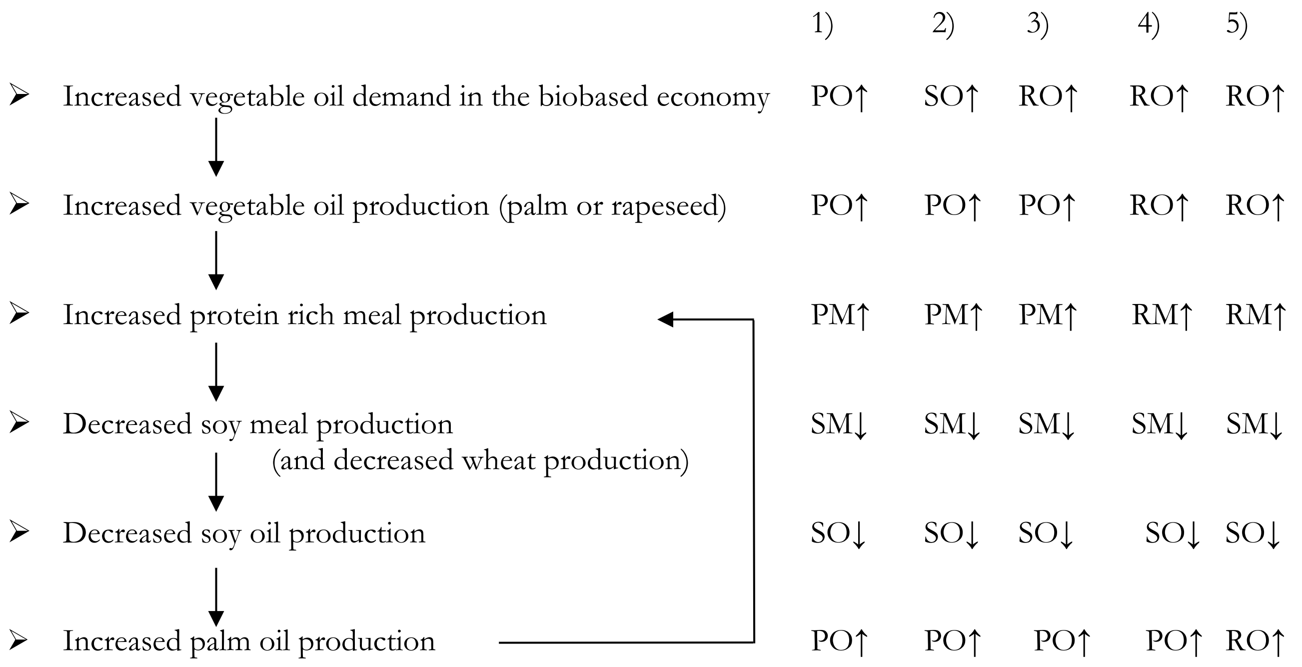
All three oil crops involved in this study provide meal which will be used as animal feed, in Europe mostly in compound feeds. Therefore, production of these oil crops will have consequences for the use of other meals and therefore for the production of other crops. These consequences will be different for the different oil crops since the ratio between oil and meal produced is different: high for palm, low for soy bean and intermediate for rapeseed (see Table 3). Hence, increased oil demand for use in the biobased economy without increased demand for meal will generally lead to more production of palm oil and/or less production of soy oil because otherwise an overproduction of meal would be created. Due to the low price-elasticity of meals (Reinhardt & Zah, 2009) this would lead to a price fall in especially soy bean. Increased use of palm oil in the biobased economy (case 1, see next page) has minor consequences; only a small amount of meal is produced, leading to a small reduction in soy bean production. Increased use of soy oil in the biobased economy is possible and since palm oil is currently the global marginal oil (Schmidt & Weidema, 2008), the most probable consequence will be a shift in the use of oil for other purposes from soy oil to palm oil (case 2). Similarly, increased use of rapeseed oil in the biobased economy will also most probably lead to an increased production of palm oil (case 3). In these three cases, the increased demand for vegetable oil is completely supplied by increased production of palm oil, eventually used for different purposes and this makes the cases principally identical. Alternative scenarios with increased rapeseed production (cases 4 and 5), however, seem also relevant since it is produced in other climatic conditions and rapeseed functioned as the world’s marginal oil crop until only a few years ago (Schmidt & Weidema, 2008). In these cases the increased rapeseed meal production will replace soy meal production (and wheat production to counterbalance protein and energy contents, see Table 4). The decrease in soy oil production will be replaced by an increased palm oil production (case 4) or by an increased rapeseed oil production (case 5). Case 4 is a standard system expansion starting with replacing a co-product for a marginal product, case 5 assumes rapeseed to be the global marginal oil, a situation that could occur when further expansion of palm oil production becomes restricted. For soybean oil no standard system expansion is presented because it results in data equal to the system expansion of palm oil since the soy meal produced will replace soy meal with as result an indirect replacement of soy oil to be used in the biobased economy with palm oil to be used for other purposes, showing the same consequences as a direct replacement.

The different cases are schematically illustrated in Figure 6. This figure shows a feedback loop: replacing soy bean oil by palm oil results in the production of palm kernel expeller, on its turn again resulting in decreased production of soy meal (Dalgaard *et al.*, 2008). The quantitative importance of this feedback, however, is small since the oil production of 1 ha soy bean can be replaced by 0.12 ha palm and 0.12 ha palm produces only circa 50 kg palm kernel expeller while 1 ha of soy bean produces almost 2000 kg soy meal. In the case of rapeseed oil being the marginal oil (case 5), the feedback loop is more important since rapeseed produces much more meal compared with oil palm. Since this case is only used for the production of rapeseed oil this problem can be solved by introducing a net rapeseed oil production which is the difference between the total production and the part needed to compensate for the decreased soy oil production. In this case the decreased soy oil production does not lead to increased oil production but to a lower quantity of rapeseed oil available for use in the biobased economy.

It should be noted that the interactions are not absolute and not instantly. Still, the generally accepted regarding of palm oil as the marginal vegetable oil implies that (in time) changes in the total demand for vegetable oil will largely comply with changes in the production of palm oil. For reasons of simplicity, in our scenarios this exchange of oils will be regarded as occurring for 100%.

Summarising five cases were established of which 1, 2 and 3 have identical consequences:

1) Use of palm oil; reduced soy oil production is compensated by palm oil production
2) Use of soy oil, causing increased palm oil production; reduced soy oil production is compensated by palm oil production
3) Use of rapeseed oil, causing increased palm oil production; reduced soy oil production is compensated by palm oil production
4) Use of rapeseed oil, causing increased rapeseed oil production; reduced soy oil production is compensated by palm oil production.
5) Use of rapeseed oil, causing increased rapeseed oil production; reduced soy oil production is compensated by rapeseed oil production.



PO: palm oil; SO: soy oil; RO: rapeseed oil; PM: palm kernel meal; SM: soy meal; RM: rapeseed meal

Figure 7, Interactions of increased vegetable oil demand with crop production.

Table 3, Composition of oil crops and wheat in % of dry matter

	Oil	Meal	Crude protein in meal
Palm	34.4	3.7	16.5
Soy bean	22	78	48
Rapeseed	45.5	54.5	34
Wheat	--	100	13

The meals of the different oil crops do not have identical compositions and are therefore not simply exchangeable. Since soy meal has the highest protein to energy ratio of the oil crop meals considered, the other meals are equivalent to a combination of soy meal and energy rich feedstock, like barley (Dalgaard *et al.*, 2008) or wheat (Lywood *et al.*, 2009). The substitution ratios between soy meal and other feed components depend on the animal type to be fed: beside differences in protein and to a smaller extent in energy content also the digestibility of the protein and the energy of the different meals are different. The digestibility is animal type dependent and moreover, due to the presence of different inhibitive compounds, this dependence is different for the different meals. Since measured digestibility is depending on other feed components (Lywood *et al.*, 2009), the figures of Table 4 are subject to uncertainty. The weighted average in Table 4 is based on the weighted total production of compound feed for the three different animal types without taking different contents of meal in different feeds into account. Probably in this way the importance of ruminants is overestimated because ruminants usually are fed low protein compound feed since their other feed components, like grass, are mostly protein rich.

Based on the 'weighted averages' from Table 4 estimates were made for the net land use of oil production. This net land use is defined as the land used for the production of an amount of oil, minus the land no longer used due to replacement of soy meal and wheat, plus the land used for the production of palm oil needed to replace the soy oil no longer produced. For this calculation yield levels according to Table 5 were used.

Table 4, Substitution ratios of oil crop meals for use in animal feed (in kg kg^{-1} fresh weight).

		Palm kernel expeller[a]	Rapeseed meal[a]
Ruminants	Wheat	0.812	0.211
	Soy meal	0.158	0.658
Pigs	Wheat	0.452	0.176
	Soy meal	0.106	0.563
Poultry	Wheat	n.a.	0.058
	Soy meal	n.a.	0.607
Weighted average EU[b]	Wheat	0.606	0.145
	Soy meal	0.128	0.605

[a]: after Lywood *et al.*, 2009.
[b]: weighted average of use in feed for ruminants, pigs and poultry in EU compound feed market. Average is weighted after total production, not after quantity of protein rich meal used.
n.a.: not applicable.

3.4 Scenarios: 'straw for energy' and 'common practice'

In our default calculations we assume a fully developed biobased economy, involving energy production from straw of soybean, rapeseed and wheat . These default calculations are presented in Chapter 6. In Chapter 6 we also present the results of a second calculation which is more in line with current agricultural practices. In this calculation straw is assumed to be left in the field because energy production from straw is not yet economically feasible. Since the use of palm oil production residues for energy production and composting is already most common practice and no data are available for eventual energy production from palm wood, the two scenarios do not differ for palm oil production.

In the calculations in Bos *et al.* (2010) straw was used to generate energy in an industrial CHP installation where the heat was used for processing of crops while an electricity surplus was delivered to the public electricity grid. However, in the current study this option would involve long distance transport of straw which is economically (and environmentally) not feasible. As an alternative option for energy production the straw is now supposed to be combusted in a regional biomass combustion plant which can generate more electricity (30% of the energy content of straw) but will mostly lack an opportunity for efficient use of the heat produced. Electricity from straw is supposed to replace NREU with an efficiency of 2.99 MJ MJ_{el}^{-1} and to have a GHG emission reduction of 116 g CO_2-eq MJ_{el}^{-1}, representing average electricity production from non-renewable sources in West Europe according to IEA Energy Balances (2003). In both scenarios the meals are used as feed components and palm wood is used as timber or fire-wood, although the effects of the latter are not quantified.

Although straw is a crop residue, it should not be regarded as a waste. Straw input gives an essential contribution to maintaining the organic matter content of the soil. Organic matter has various important functions in a soil (prevention of erosion, nutrient supply, improving the water holding capacity). However, it is hard to estimate the effect of regularly harvesting straw on the organic matter content of a soil and it depends strongly on soil type, slope, climate and management what organic matter content should be regarded and maintained as a sustainable minimum. Therefore, the default scenario (with harvest of straw) cannot be considered unsustainable at forehand but it certainly brings a risk of decreasing the organic matter content of the soil to an undesirably low level.

Furthermore, a lower soil organic matter content implies less carbon storage and an additional CO_2 emission until a new equilibrium organic matter content is reached. This kind of emission is recognised in GHG balances as an effect of land use change and the difference in carbon storage is then calculated as a GHG emission occurring over a period of twenty years. This kind of emission as an effect of changes in agricultural practices is normally neglected in GHG balances. It will not be part of our calculations but it will be addressed in the discussion section.

3.5 Modelling and input data for crop cultivation and production of vegetable oil

Calculations of energy use and GHG emissions during crop production, transport and oil extraction were made with the model ‘E-CROP’, which is developed in the past years to assess a number of sustainability aspects of biomass-bioenergy chains (Conijn & Corré, 2009; Corré & Conijn, 2011). In the calculations four steps are distinguished: 1) agricultural production, 2) transport of products and agricultural co-products (crop residues, e.g. straw) to a processing plant, 3) extraction of vegetable oil and 4) using the agricultural co-products for energy production and using the processing co-products as animal feed. Land use changes, direct or indirect, can have large effects on GHG emissions, but were not yet taken into consideration because of their complicated effects on the GHG emissions (Conijn & Corré, 2009). Also the effects of changes of the current agricultural practices on the soil carbon dynamics were not taken into account in the calculations. In future research these aspects can be incorporated to present a more complete picture of the effects on the GHG emissions.

Model input data for agricultural production were taken from BioGrace (2011) for palm oil and soybean and from Conijn *et al.* (2011) for rapeseed. As input data for rapeseed the average of the values for France and Germany, the main rapeseed producing countries in North-West Europe, were taken. For wheat, input data were established in a comparable way, also as average of data for France and Germany. A summary of the model input data and on the substitution (based on data from Lywood *et al.*, 2009) is presented in Table 5.

3.6 Results

A summary of the model output data for current agricultural practices is presented in Table 6 for the crops involved and in Table 7 for the cases studied. In Table 8 additional data for electricity generation are presented. In Table 9 the credits from electricity generation are taken into account and finally in Table 10 a summary of the model output data for a fully developed biobased economy is presented.

The most obvious result of the calculations is the exact same figures for palm oil, soy oil and rapeseed oil per ton oil produced in cases 1, 2 and 3. Its reason is already explained in Section 3.3: due to the interactions between different oil crops the increased demand for vegetable oil without increase of the demand for feed protein leads in all three cases to production of palm oil, the world's current marginal vegetable oil. Moreover, since the production of palm oil delivers also a small amount of meal that partly can replace soy meal, increased oil production leads even to a small decrease of the soybean production. When rapeseed oil is used and actually produced (cases 4 and 5), the interaction is more complicated and the results are different. Generally the use of rapeseed oil results in appreciably increased GHG emission and land use but only slightly increased energy use per ton oil produced, compared with palm oil. These effects are more pronounced in case 5 compared with case 4. Reasons for these differences are the long distance transports for palm oil (high energy use), the high fertiliser N use per ton of oil in rapeseed (high emission of N_2O) and the low oil yield of rapeseed compared to palm (high land use).

Using straw for electricity production decreases NREU and GHG emission from rapeseed oil production (NREU even to a negative value; cases 4 and 5) but it causes a small increase in NREU and GHG emission in the other cases. When rapeseed oil is produced, more straw is harvested, although the increased use of rapeseed straw is partly compensated by less use of wheat straw and soybean straw. When palm oil is produced, the interactions cause even a small decrease in the use of wheat straw and soybean straw for electricity while this scenario does not take an eventual more efficient use of co-products of oil palm for energy production into account. More efficient heat and power production of oil mill residues could decrease NREU and GHG emission from palm oil production but quantitative data on its extent are not available. Also using palm wood for electricity production would decrease NREU and GHG emission, when palm oil plantations are renewed after 25 years of production the wood production is estimated at circa 75 ton dry matter ha^{-1} (Corley & Tinker, 2003). With this amount of potential energy, the electricity credits for palm would be in the same order per ha as for rapeseed. Per ton oil, however, the electricity credits for rapeseed straw would still be higher and the energy use per ton oil would also still be lower in rapeseed.

Consequently, the land use per ton oil produced is the same for the use of palm oil, soy oil or rapeseed oil. It is higher when rapeseed is actually produced, 50% higher in case 4 and 60% higher in case 5.

Table 5, Input and substitution data for the calculation of energy input, GHG emission and land use in the production of vegetable oil.

	Unit	Palm S-E Asia	Soy bean Brazil	Rapeseed Europe	Wheat Europe
Yield	ton ha^{-1} yr^{-1}	19.00	2.80	3.55	7.20
Dry matter product.	ton ha^{-1} yr^{-1}	12.54	2.38	3.20	6.26
Crude oil contents	% of d.m.	34.4	22	45.5	--
Crude oil yield	ton ha^{-1} yr^{-1}	4.31	0.52	1.46	--
Straw yield	ton ha^{-1} yr^{-1}	0[1]	2.50	2.50	4.00
Straw d.m.	ton ha^{-1} yr^{-1}		2.13	2.13	3.40
Transport distance	km truck	20[b]	700[d]	100[d]	100[d]
	km truck	150[c]			
	km train	0		500[d]	500[d]
	km ship	10000[c]	10000[d]		
	km truck	--	50[g]	50[g]	50[g]
Meal production (d.m.)	ton ha^{-1} yr^{-1}	0.47	1.86	1.74	--
Soy meal replaced fresh	ton ha^{-1} yr^{-1}	0.06		1.04	--
Wheat replaced fresh	ton ha^{-1} yr^{-1}	0.30		0.26	--
Palm oil produced[e]	ton ha^{-1} yr^{-1}	0.017		0.29	--
Electricity from straw	GJ ha^{-1}	0	10.8	10.8	17.3
Heat[f]	GJ ha^{-1}	0	18.1	18.1	28.9

[a]: Co-product fresh fruit pulp is supposed to deliver the energy needed for oil extraction and co-product wood is left out of calculations due to lack of data.

[b]: Fresh fruit bunches.

[c]: Crude oil only.

[d]: Seeds.

[e]: Produced to replace the soy oil not produced due to replacing soy meal.

[f]: Heat is presumed not to be utilised.

[g]: Straw.

Table 6, Energy input, GHG emission and land use in the production of agricultural crops according to current agricultural practices.

	Unit	Palm S-E Asia	Soy bean Brazil	Rapeseed Europe	Wheat Europe
NREU					
Agriculture	GJ ha^{-1}	13.3	5.3	11.0	10.2
Transport	GJ ha^{-1}	6.3	8.0	1.7	3.5
Oil extraction	GJ ha^{-1}	0.0	3.0	4.2	--
NREU/ha	GJ ha^{-1}	19.6	16.2	16.9	13.8
NREU/ton	*GJ* ton^{-1} *oil*	*4.6*	*31.2*	*11.6*	--
GHG emission					
Agriculture CO_2	kg CO_2-eq. ha^{-1}	790	390	650	620
Agriculture N_2O	kg CO_2-eq. ha^{-1}	1050	270	1810	1630
Transport	kg CO_2-eq. ha^{-1}	490	590	110	230
Oil extraction	kg CO_2-eq. ha^{-1}	0	210	300	--
GHG/ha	kg CO_2-eq. ha^{-1}	2330	1460	2870	2480
GHG/ton	*kg* CO_2*-eq.* ton^{-1} *oil*	*540*	*2810*	*1970*	--
Land use					
Oil production	ha ha^{-1}	1.00	1.00	1.00	
	ha ton^{-1} *oil*	*0.232*	*1.92*	*0.685*	

Table 7, Energy input, GHG emission and land use in the production of vegetable oil according to current agricultural practices.

	Unit	Case 1, 2, 3	Case 4	Case 5
NREU				
NREU/ha	GJ ha^{-1}	19.6	16.9	16.9
NREU/ton	*GJ ton^{-1} oil*	*4.6*	*11.6*	*11.6*
Credit meal	GJ ha^{-1}	-1.1	-8.4	-9.7
Total/ha	GJ ha^{-1}	18.5	8.5	7.2
Total/ton	*GJ ton^{-1} oil*	*4.3*	*5.9*	*6.2*
GHG emission				
GHG/ha	kg CO_2-eq. ha^{-1}	2330	2870	2870
GHG / ton	*kg CO_2-eq. ton^{-1} oil*	*540*	*1970*	*2450*
Credit meal	kg CO_2-eq. ha^{-1}	-160	-780	-920
Total/ha	kg CO_2-eq. ha^{-1}	2170	2090	1950
Total/ton	*kg CO_2-eq. ton^{-1} oil*	*500*	*1440*	*1670*
Land use				
Oil production	ha ha^{-1}	1.00	1.00	1.00
	ha ton^{-1} oil	*0.232*	*0.685*	0.685
Soy replaced	ha ha^{-1}	-0.032	-0.557	-0.557
Wheat replaced	ha ha^{-1}	-0.048	-0.042	-0.042
Palm produced	ha ha^{-1}	0.004	0.068	0
Net palm[a]			0.062	0
Net land use	ha ha^{-1}	0.923	0.463	0.401
	ha ton^{-1} oil	*0.214*	*0.319*	*0.343*

[a]: Net land use for palm oil production replacing decreased soy oil production (0.923 * land use).

Table 8, Energy input, GHG emission and land use in the production of agricultural crops: effects of electricity production from straw.

	Unit	Palm S-E Asia	Soy bean Brazil	Rapeseed Europe	Wheat Europe
Energy input					
NREU straw[a]	GJ ha^{-1}	0.0	3.0	3.0	4.1
Electricity prod.	*GJ ha^{-1}*	*-0.0*	*-10.8*	*-10.8*	*-17.3*
Electricity credit	GJ ha^{-1}	-0.0	-32.4	-32.4	-51.8
GHG emission					
GHG straw[a]	kg CO_2-eq. ha^{-1}	0	75	100	110
El. prod. em. red	kg CO_2-eq. ha^{-1}	-0	-1260	-1260	-2010

[a]: Collecting, transport, processing and avoided crop residue input of straw removal.

[b]: NREU/GHG indirect: net electricity credit or net GHG emission reduction from straw of soy bean and wheat that are replaced due to the extra meal production as result of the increased oil production.

Table 9, Energy input, GHG emission and land use in the production of vegetable oil: effects of electricity production from straw.

	Unit	Case 1, 2, 3	Case 4	Case 5
Energy input				
NREU straw[a]	GJ ha^{-1}	0.0	3.0	3.0
Electricity prod.	*GJ ha^{-1}*	*-0.0*	*-10.8*	*-10.8*
Electricity credit	GJ ha^{-1}	-0.0	-32.4	-32.4
NREU indirect[b]	GJ ha^{-1}	3.3	18.6	18.4
NREU total.	GJ ha^{-1}	3.3	-10.8	-11.0
	GJ ton^{-1} oil	*0.8*	*-7.4*	*-9.4*
GHG emission				
GHG straw[a]	kg CO_2-eq. ha^{-1}	0	100	100
El. prod. em. red	kg CO_2-eq. ha^{-1}	-0	-1260	-1260
GHG indirect[b]	kg CO_2-eq. ha^{-1}	130	750	740
GHG emission	kg CO_2-eq. ha^{-1}	130	-410	-420
total	*kg CO_2-eq. ton^{-1} oil*	*30*	*-280*	*-360*

[a]: Collecting, transport, processing and avoided crop residue input of straw removal.

[b]: NREU/GHG indirect: net electricity credit or net GHG emission reduction from straw of soy bean and wheat that are replaced due to the extra meal production as result of the increased oil production.

Table 10, Energy input, GHG emission and land use in the production of vegetable oil, including electricity production from straw.

	Unit	Case 1, 2, 3	Case 4	Case 5
Energy input				
Current practice	GJ ha^{-1}	18.5	8.5	7.2
Electricity straw	GJ ha^{-1}	3.3	-10.8	-11.0
Total	GJ ha^{-1}	21.7	-2.3	-3.8
Total	*GJ ton^{-1} oil*	*5.0*	*-1.6*	*-3.3*
GHG emission				
Current practice	kg CO_2-eq. ha^{-1}	2170	2090	1950
Electricity straw	kg CO_2-eq. ha^{-1}	130	-410	-420
Total	kg CO_2-eq. ha^{-1}	2290	1680	1530
Total	*kg CO_2-eq. ton^{-1} oil*	*530*	*1160*	*1310*

4 Vegetable oil based products

Within this study the following products were analyzed: biodiesel, polyols (a raw material for polyurethane foams) and a resin.

4.1 Biodiesel (FAME)

Vegetable oils are widely used for biodiesel production. The environmental benefit of this chain is subject of extensive debate. An important issue of the debate focusses on the allocation of emissions to the press cake (Hoefnagels *et al.*, 2010). Allocation based on mass gives a significantly different result compared to allocation based on price. Allocation based on price will lead to results that are depending on constantly changing markets for oil and protein rich meals. The RED (Renewable Energy Directive) states that allocation should be based on energy content, which will give yet another result. With system expansion the issue of allocation can be circumvented.

Another important issue of debate is on the indirect effects caused by land use change (Reinhardt and Falkenstein, 2011). These indirect effects are very difficult to pinpoint and therefore are rarely included in the analysis, although they can have dramatic effects on the GHG balance.

Biodiesel produced from soy and palm oil is of inferior quality compared to biodiesel from rapeseed oil in cold conditions. Especially in higher blends, biodiesel from palm and soy will cause clogging of fuel lines and fuel filters. In tropical regions and in adapted trucks (with a pre-heating system for the fuel) the use of these biodiesels is fairly possible.

4.2 Polyols

Vegetable oils can serve as a substitute for polyols in polyurethane foams. Some manufacturers state that foams based on vegetable oil provide even better quality than fossil based foams (Arkansas Soybean Promotion Board, 2010). Polyurethane foams are usually made of long and linear polyether chains that are connected by urethane moieties. A small amount of trivalent alcohols (e.g. glycerol) is added to create a network structure.

Vegetable oils contain double bonds. These double bonds are epoxidized and then hydrolyzed so that two alcohol groups are formed at the site of the double bond. Thus, the vegetable oils provide long chains that are kept together by glycerol and can replace both glycerol and polyethers in fossil oil based polyurethane foams. To keep control of the chain length and the degree of cross linking, the manufacturer often adds petroleum-based polyols. The urethane moiety is produced from fossil resources. Eventually up to 20% of the foam is from renewable resources.

In this study the production of the polyol as a semi-finished product will be studied. This half fabricate will be up to 96% of biobased origin. The biobased polyols studied in this report are produced by BioBased Technologies (Springdale, Arkansas).

In practice, palm oil is not suitable for polyol production as the fatty acids do not have sufficient unsaturated bonds.

4.3 Resin

Soy oil can be used to produce thermoset resins. Ashland produces such a resin (ENVIREZ 1807) from maleic anhydride, ethanol, soy bean oil, glycol and styrene (Ashland 2011a, Ashland 2011b). The final product contains 12% soy oil. Ashland has provided process and composition data on the production of this product to Omni Tech International for their LCA analysis.
In practice palm oil is not suitable for resin production as the fatty acids do not have sufficient unsaturated bonds. Rape seed oil however could well be used in these applications.

4.4 Product chain analysis (Omni Tech International)

In Figure 8, the product chains that were analyzed by Omni Tech International (2010) are given. Data on these chains (Table 11) can be found in the designated tables in the Omni Tech International report (2010). Based on these chain data, the NREU and GHG emission data for the individual processes were calculated (Table 13) (see also Appendix A.4).

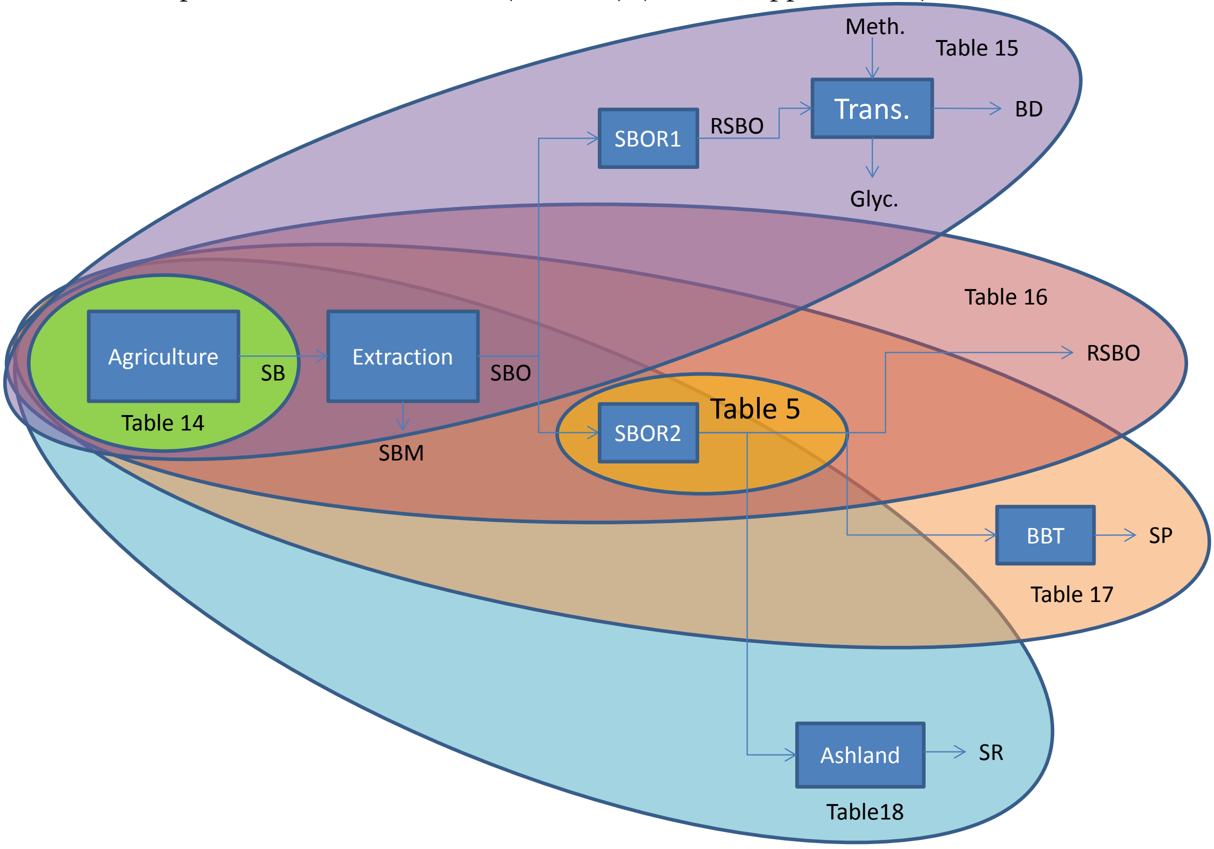


Figure 8, Production chains and related tables in Omni Tech International report (2010)

Ashland	Manufacturer of Soy based Resin
BBT	BioBased Technologies: Manufacturer of Soy based Polyol
BD	BioDiesel
Glyc.	Glycerol
Meth.	Methanol
RSBO	Refined Soy Bean Oil
SB	Soy Beans
SBM	Soy Bean Meal
SBO	Soy Bean Oil
SBOR	Soy Bean Oil Refinery
SP	Soy Polyol
SR	Soy based Resin

Table 11, Production chain data (cradle to gate) used for calculations

From	To	GHG em.	Unit	NREU	Unit	Reference*
Agriculture	Soy Beans	-1200	kg/ton SB	1800	MJ/ton SB	Table 14
Agriculture	Soy Bean Oil	-2293	kg/ton SBO	4048	MJ/ton SBO	**
Agriculture	Refined Soy Bean Oil	-2400	kg/ton RSBO	4300	MJ/ton RSBO	Table 16
Agriculture	Biodiesel	-2100	kg/ton BD	8700	MJ/ton BD	Table 15
Agriculture	Soy Polyol	-1400	kg/ton SP	16000	MJ/ton SP	Table 17
Agriculture	Soy Resin	4100	kg/ton SR	43000	MJ/ton SR	Table 18

*Reference to respective tables in Omni Tech International (2010)

**Calculated from RSBO data and SOBR2 data found in table 5 of Omni Tech International (2010), see also Appendix A.3

Omni Tech International has included biobased carbon as a negative CO_2 emission in their data. These negative emissions were excluded from the data calculated in Table 13 by correction with the carbon content of the products (Table 12) (see also Appendix A.4).

Table 12, Biobased CO_2 stored in product

Product	CO_2 stored	Unit	Reference*
Soy Beans	1561	kg/ton SB	Page 10
Soy Bean Oil	2823	kg/ton SBO	Table 13
Refined Soy Bean Oil	2955	kg/ton RSBO	Table 13
BioDiesel	2823	kg/ton BD	Table 13
Soy Polyol	2689	kg/ton SP	Table 13
Soy Resin	355	kg/ton SR	Table 13

*Reference to Omni Tech International report (2010)

The present study takes the non-renewable energy content of the product as a positive contribution to the NREU value. The Soy Resin has only a small proportion of soy oil and a large portion of fossil based components (e.g. 30% of styrene). The non-renewable energy content (calorific value) of the resin is estimated at 41.9 MJ/kg (Pollack, 2011). This explains the much higher NREU number for Soy Resin in Table 13 compared to Table 11.

Table 13, Process unit data calculated from Omni Tech International data

From	To	GHG em.	Unit	NREU	Unit
Agriculture	Soy Beans	361	kg/ton SB	1800	MJ/ton SB
Soy Beans	Soy Bean Oil	161	kg/ton SBO	2210	MJ/ton SBO
Soy Bean Oil	Refined Soy Bean Oil	7	kg/ton RSBO	112	MJ/ton RSBO
Soy Bean Oil	BioDiesel	256	kg/ton BD	5132	MJ/ton BD
Refined Soy Bean Oil	Soy Polyol	784	kg/ton SP	12087	MJ/ton SP
Refined Soy Bean Oil	Soy Resin	4388	kg/ton SR	84684	MJ/ton SR

Table 10 and WUR-PRI data as presented in Chapter 3 were used to calculate the NREU and GHG emissions of biobased products from palm oil, soy oil and rapeseed oil as shown in Appendix A.5 and A.6

5 Fossil reference components

In order to investigate the reduction of NREU and GHG emissions, fossil reference components are needed for comparison. Diesel produced from crude oil via oil refinery is used as reference for biodiesel. A petroleum based polyol was used as reference for the biopolyol. The fossil reference polyol is produced from propylene oxide, ethylene oxide and glycerin. A standard unsaturated polyester resin manufactured by Ashland Composite Polymers company is used as reference product for the bioresin. More precisely, the process energy and formulation data to produce Ashland's propylene glycol maleate were used (Omni Tech International, 2010). The reacted resin is diluted in styrene to produce the mixture as sold to the costumers.
The NREU and GHG emission data for the fossil reference components were taken from the Omni Tech International (2010) report (Table 14 and Table 15). An estimate of the incorporated non-renewable energy (calorific value) was added to these numbers to comply with the starting points of the present study following the methodology of Bos *et al.* (2011).

Table 14, GHG emissions for fossil reference components

	kg CO_2/ton	Reference*
Diesel	660	table 15
Polyol	4100	table 17
Resin	4700	table 18

*Reference to respective tables in Omni Tech International report (2010)

Table 15, NREU for fossil reference components

	NREU	MJ/kg	Reference*
Diesel	Process	8.1	table 15
	Incorporated	44.8	Wikipedia (2011a)
	Total	**52.9**	
Polyol	Process	55.0	table 17
	Incorporated	29.8	estimate from PEG and PPG, table 12
	Total	**84.8**	
Resin	Process	47.0	table 18
	Incorporated	46.5	Pollack (2011)
	Total	**93.5**	

*Reference to respective tables in Omni Tech International report (2010)

The NREU and GHG emission data for fossil diesel processing are considerably higher than used in the sugar study by Bos *et al.* (2011). Bos *et al.* have assumed that 7% of the energy in the product was used for production of gasoline (3.1 MJ/kg instead of 8.1 MJ/kg). The number used by Omnitech is close to the numbers used in the Ecoinvent database, the number used by Bos *et al.* is clearly lower. Because the processing energy in the oil refinery is small compared to the incorporated NREU, this deviation will not influence the final conclusions.

6 Results and discussion

6.1 Production of vegetable oils (system expansion)

The production of vegetable oils was evaluated according to the method described in chapter 3. Credits for meal production were calculated via system expansion. The results were calculated for current practice (Figure 9a till Figure 11a) and for future practice (where the straw from soy, rapeseed and wheat is expected to be used for production of electricity) (Figure 9b till Figure 10b).

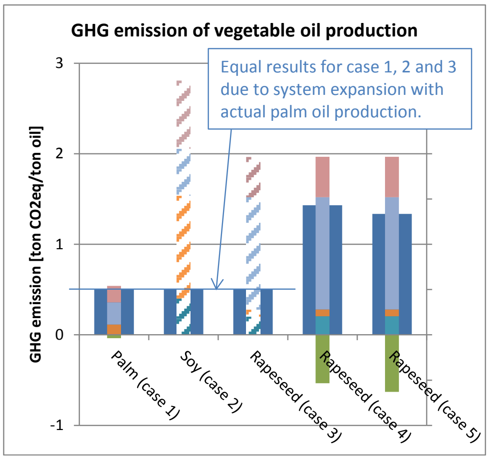


Figure 9a, GHG emissions current practice

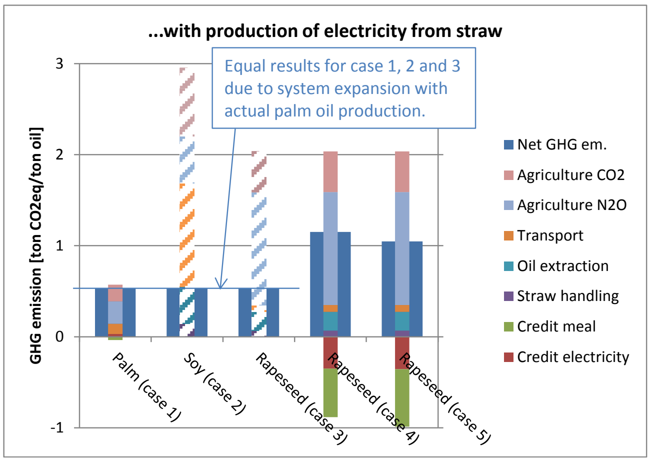


Figure 9b, GHG emissions fully developed biobased economy

Narrow bars show GHG emissions per ton oil. Striped bars give *pro memori* soy and rapeseed production data[1], credits are not given as soy and rapeseed oil are actually not produced; the net results are calculated via system expansion with production of palm oil. Negative emissions (credits) are calculated via system expansion to account for the co-products (oil, meal and electricity). Wide bars show resulting net emissions. Cases are described in paragraph 3.3. Left graphs (a) show results for current practice; right graphs (b) show results for fully developed biobased economy scenario, where straw will be used for production of electricity.

---

[1] *GHG, NREU and area of actual soy bean oil and rapeseed oil production are high because soy bean and rapeseed have a high protein content. A large part of GHG, NREU and area would have been allocated to the protein rich co-product if mass allocation would have been applied.*

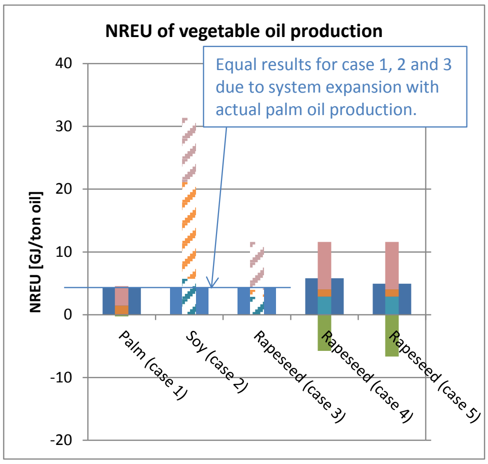


Figure 10a, NREU current practice

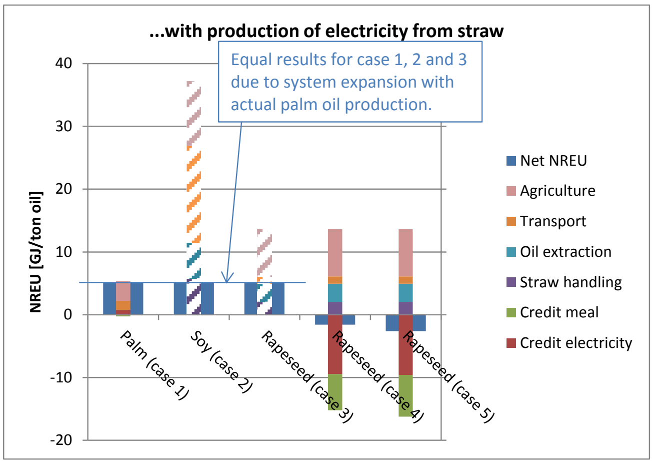


Figure 10b, NREU fully developed biobased economy

Narrow bars show Non Renewable Energy Usage per ton oil. Striped bars give *pro memori* soy and rapeseed production data[1], credits are not given as soy and rapeseed oil are actually not produced; the net results are calculated via system expansion with production of palm oil. Negative NREU (credit) is calculated via system expansion to account for the co-products (oil, meal and electricity). Wide bars show resulting net NREU. Cases are described in paragraph 3.3. Left graphs (a) show results for current practice; right graphs (b) show results for fully developed biobased economy scenario, where straw will be used for production of electricity.

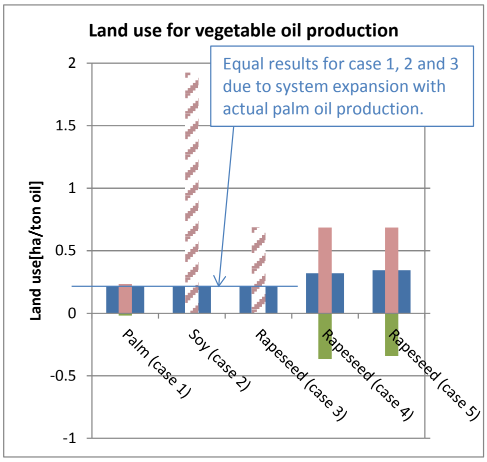


Figure 11a, Land use current practice

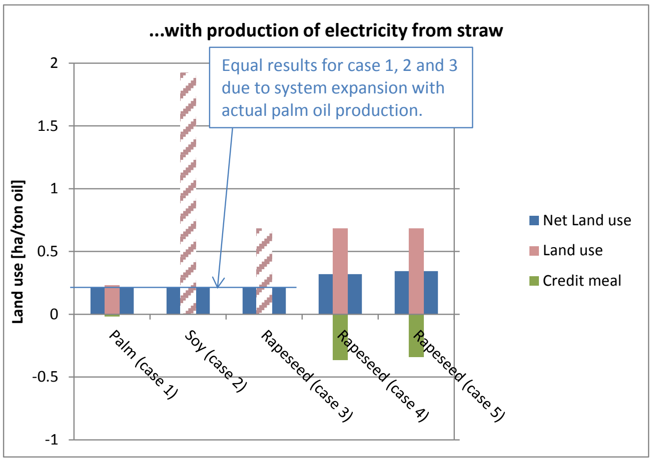


Figure11b, Land use fully developed biobased economy

Narrow bars show agricultural area needed per ton oil. Striped bars give *pro memori* soy and rapeseed production data[1], credits are not given as soy and rapeseed oil are actually not produced; the net results are calculated via system expansion with production of palm oil. Negative land use is calculated via system expansion to account for the co-products (oil, meal and electricity). Wide bars show resulting net land use. Cases are described in paragraph 3.3. Left graphs (a) show results for current practice; right graphs (b) show results for fully developed biobased economy scenario, where straw will be used for production of electricity.

Through system expansion, the net NREU, the net GHG emission and the net land use of palm oil production (case 1) are equal to the figures for soy (case 2) and rapeseed oil (case 3) when replaced by increased palm oil production (as indicted by the blue lines).

The net GHG emission of rapeseed oil production (case 4 and case 5) is much higher than the net GHG emission from palm oil. This is mainly caused by the high N fertilizer input and consequent N_2O emissions. The net NREU and net land use for rapeseed production are only slightly higher than palm oil production. Taking into account that the growth season for palm is year round and that the growth season of rapeseed is much shorter, the results for rapeseed are very good.

If electricity production from straw is included, the GHG emission for the production of rapeseed oil decreases and the NREU even becomes negative (i.e. production of rapeseed oil becomes an energy producing process) (see also Table 14 line 5). This effect is caused by the fact that rapeseed produces a considerable amount of straw. This straw is assumed to be burnt for electricity production and thus reduces the NREU of the system.

For the use of palm oil (soy oil and rapeseed oil (, when the extra demand for oil is fulfilled by increased palm oil production: cases 1, 2 & 3), the use of straw for production of electricity will lead to an increase of the NREU. Although contra-intuitive, this can be explained as follows: the production of palm oil will increase. The accompanying production of palm kernel expeller will cause a small decrease of soybean and wheat production. Wheat and soybean have a considerable coproduction of straw while oil palm is supposed not to have an increased utilization of biomass in the 'full BbE' scenario and therefore the total production of electricity will decrease.

6.2 Production of vegetable oils (comparison with allocation methods)

One of the goals of the present study is to investigate the effects of different methods for accounting for co-products on NREU, GHG emission and land use. In paragraph 6.1 system expansion was used to calculate NREU, GHG emission and land use for palm, soy and rapeseed oil production. In order to explore the effect of different accounting methods on the results, the WUR-PRI data were used to calculate the NREU, GHG emission and land use for vegetable oil production with mass and economic allocation. From the Omni Tech International study, the NREU, GHG emission and land use for production of soy bean oil with mass, energy and price allocation were derived. All the resulting data were collected in Table 16, Table 17 and Table 18.

Table 16, GHG emission of vegetable oil production (ton CO_2eq/ton oil)

Line	Electricity	Accounting	Base	Allocation over	Palm	Soy	Soy (OTI)	Rapeseed
1	no	syst. exp.			0.50[a]	0.50[b]		0.50[b]/1.44[c]/1.67[d]
2	no	allocation	mass	oil and meal	0.50	0.61	0.53	0.90
3	no	allocation	energy	oil and meal	0.52	1.01		1.23
4	no	allocation	price	oil and meal		1.01	1.05	
5	yes	syst. exp.			0.53[a]	0.53[b]		0.53[b]/1.16[c]/1.31[d]
6	yes	allocation	mass	oil, meal and straw	0.50	0.50		0.61

[a]: in system expansion palm oil is produced (case 1)
[b]: in system expansion soy oil (case 2) and rapeseed oil (case 3) are replaced by palm oil (hence equal results)
[c]: in system expansion rapeseed oil is actually produced (case 4)
[d]: in system expansion rapeseed oil is the marginal oil (case 5)

Table 17, NREU of vegetable oil production (GJ/ton oil)

Line	Electricity	Accounting	Base	Allocation over	Palm	Soy	Soy (OTI)	Rapeseed
1	no	syst. exp.			4.3[a]	4.3[b]		4.3[b]/5.9[c]/6.2[d]
2	no	allocation	mass	oil and meal	4.2	6.9	4.0	5.3
3	no	allocation	energy	oil and meal	4.4	11.2		7.3
4	no	allocation	price	oil and meal		11.2	8.0	
5	yes	syst. exp.			5.0[a]	5.0[b]		5.0[b]/-1.6[c]/-3.3[d]
6	yes	allocation	mass	oil, meal and straw	4.2	6.5		4.5

[a]: in system expansion palm oil is produced (case 1)
[b]: in system expansion soy oil (case 2) and rapeseed oil (case 3) are replaced by palm oil (hence equal results)
[c]: in system expansion rapeseed oil is actually produced (case 4)
[d]: in system expansion rapeseed oil is the marginal oil (case 5)

Table 18, Area needed for vegetable oil production (ha/ton oil)

Line	Electricity	Accounting	Base	Allocation factor	Palm	Soy	Soy (OTI)	Rapeseed
1	no	syst. exp.			0.21[a]	0.21[b]		0.21[b]/0.32[c]/0.34[d]
2	no	allocation	mass	oil and meal	0.21	0.42	0.42	0.31
3	no	allocation	energy	oil and meal	0.22	0.69		0.43
4	no	allocation	price	oil and meal		0.69	0.83	
5	yes	syst. exp.			0.21[a]	0.21[b]		0.21[b]/0.32[c]/0.34[d]
6	yes	allocation	mass	oil, meal and straw	0.21	0.22		0.19

[a]: in system expansion palm oil is produced (case 1) [b]: in system expansion soy oil (case 2) and rapeseed oil (case 3) are replaced by palm oil (hence equal results) [c]: in system expansion rapeseed oil is actually produced (case 4) [d]: in system expansion rapeseed oil is the marginal oil (case 5)

The results show quite some variation depending on the allocation method used. The main differences will be discussed below.

As explained in paragraph 6.1, the NREU, GHG emissions and land use needed are equal for palm, soy and rapeseed oil when system expansion is used and soy oil and rapeseed oil are exchanged for palm oil in the market (Case 1, 2 and 3). This is not the case for mass, energy and price allocation methods. The NREU, GHG emissions and land use are considerably higher for soy and rapeseed oil if energy or price allocation are used (compare lines 2, 3, 4) compared to mass allocation. Energy and price allocation results are almost equal. Often price allocation is preferred over mass allocation as it will give a better reflection of market circumstances. However, the possibility of another oil (such as palm oil) being produced is not at all taken into consideration. System expansion can reveal the results of such market shifts.

The results from Omni Tech International show comparable GHG emissions (compare line 2) and considerably lower values for NREU. WUR-PRI has included the transport of soy beans from Brazil to Europe in their calculations whereas the Omni Tech study assumes production and processing in the United States of America. As transport will contribute more to NREU than to GHG emissions this can largely explain the different results.

If production of electricity from straw is assumed, the fundamental difference between system expansion and other accounting methods becomes evident. Using mass allocation, the NREU and GHG emission for soy oil production decreases (compare line 6 with line 2). Using system expansion, the NREU and GHG emission for soy oil increases slightly (compare line 5 with line 1). System expansion assumes that even though the demand for soy oil is increased, the actual production of soy oil will decrease (as palm oil is grown instead). (Mass) allocation methods assume that soy is indeed produced and that the co-produced straw will result in lower NREU and GHG emission. Similar issues are seen with GHG emissions and with rapeseed oil production (case 3). These issues illustrate that allocation methods cannot take market shifts into account and therefore the use of system expansion, despite its uncertainties, is to be preferred.

As shown in paragraph 6.1, the NREU for actual rapeseed production (case 4 and case 5) is negative if electricity production is assumed (table 14 line 5). Using mass allocation methods (where negative greenhouse gas emissions through production of renewable electricity are not included) this is not the case (line 6). It should be noted that the production of electricity from straw is an efficient way to reduce NREU, but it is also an expensive way. Costs were not included as an impact factor in the analysis, and therefore it must be kept in mind that the costs of different scenarios can be very different and that high costs might hinder realization of expensive scenarios (i.e. burning of straw for production of electricity as assumed in system allocation (line 5).

It is important to keep in mind that the emission of greenhouse gasses caused by (indirect) land use changes (LUC) are not taken into account in the present study. As these emissions can be very high for newly developed oil palm plantations, the GHG emissions caused by palm oil production might be higher than indicated. Since the system expansion uses palm oil to replace soy oil the GHG emission of soy oil production will then also be higher. Soy cultivation in Brazil might also be related to higher GHG emissions from ILUC due to increased pressure on tropical rain forests. Recently IFPRI published a study on LUC of increased biofuel crop production (Laborde, 2011). In this study also a system expansion based on the exchangeability of vegetable oils was used and this resulted in almost equal LUC emissions from different oils (1860 kg CO_2-eq./ton oil for palm and rapeseed and 1930 kg CO_2-eq/ton oil for soy. A large part of these high emissions is caused by the assumption that 30% of the increased palm oil production will be located on newly reclaimed peat soils. These numbers are 3 to 4 fold higher than the numbers reported in this study (where land use change was not taken into account).

The method of system expansion will only be valid as long as some of the soy oil on the market can be replaced by palm oil e.g. as cooking oil. If the demand for soy oil goes beyond this volume, palm oil cannot further replace soy oil and another oil should fill the gap. Only a few years ago rapeseed oil was the marginal oil.

6.3 Vegetable oil based products (allocation via system expansion)

Figure 12 through Figure 17 show the NREU and GHG emissions for vegetable oil based products and their reference products (without (a) and with use of energy from straw (b)). In all cases, the vegetable oil based products perform better than their fossil reference. The reduction of GHG emissions is smaller for rapeseed because of the high demand for N fertilizer and the consequent emission of N_2O from the field.

For rapeseed based products the effect of usage of co-products for electricity production is high compared to palm oil (and soy) oil based products. This is caused by the high production of co-products from rapeseed cultivation. Production of palm also has a large volume of co-products, but it is already common practice to use these products for production of energy for oil extraction.

The NREU and GHG emissions of fossil based diesel are low and therefore, the avoided NREU and GHG emissions for biodiesel are low. The NREU and GHG emission reduction is better for more complex products such as polyol, as the fossil reference products are difficult to produce (Figure 13 and Figure 16). The production of resin needs such large amounts of fossil energy (mainly for production of the complicated fossil components such as maleic anhydride and styrene that are also part of the resin), that the contribution of the vegetable oil is hardly visible in the values expressed per ton of product. The GHG emissions per ton biobased diesel and polyol are negative due to the choice to include the amount of recently fixed CO_2 in the end product as negative emission (see Chapter 2).

If the NREU and GHG emission results are given per hectare (Figure 14 and Figure 17), the resin values are better than the biodiesel values. NREU and GHG emission values per hectare are lower for rapeseed based products. This is partially caused by the lower productivity of a crop in temperate regions (where the growing season is shorter due to low temperatures in winter) than in tropical regions. Another reason is the high usage of fertilizers (causing N_2O emissions from the field) in rapeseed cultivation.

Compared to Bos *et al.* (2011) the NREU and GHG emission reduction of vegetable oil based products are comparable with the reduction of sugar based products.

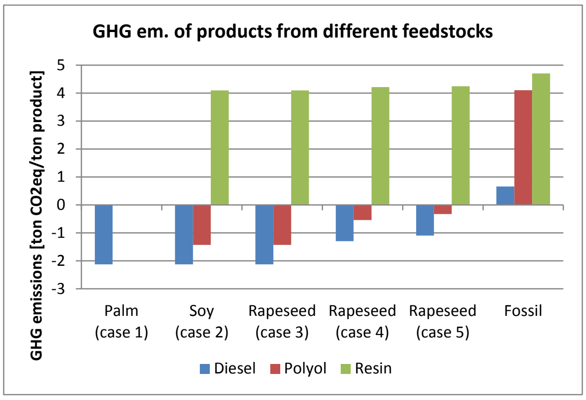


Figure 12a, GHG emission from different feedstocks

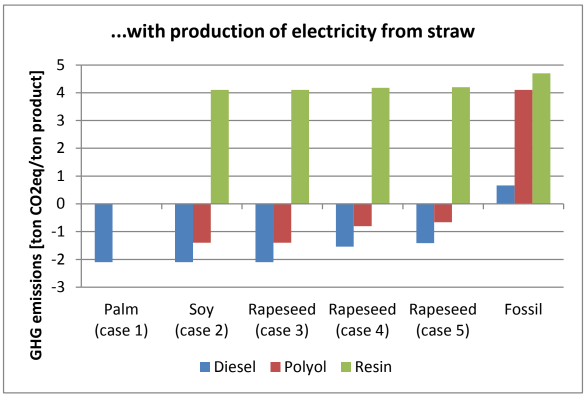


Figure 12b,..., fully developed biobased economy

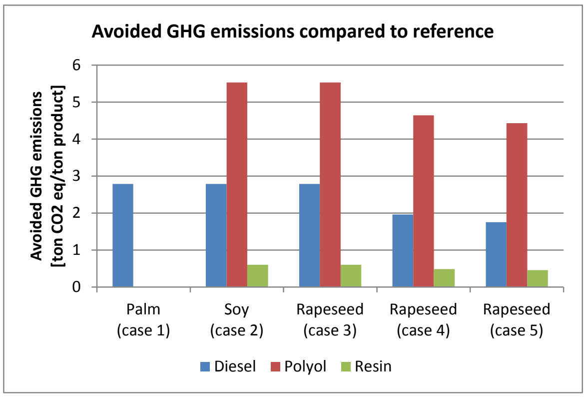


Figure 13a, Avoided GHG emission compared to reference

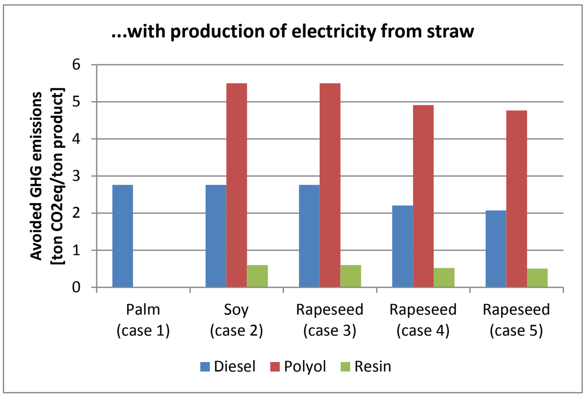


Figure 13b, …, fully developed biobased economy

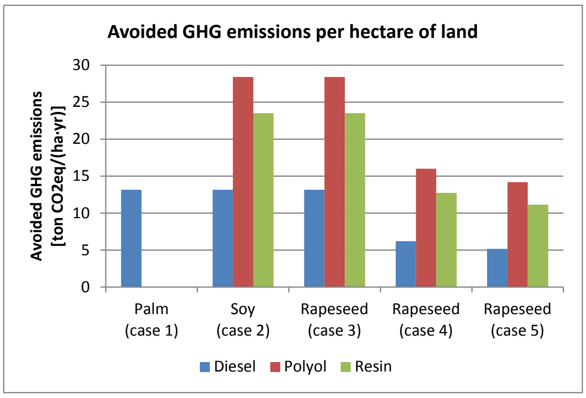


Figure 14a, Avoided GHG emission per hectare per year

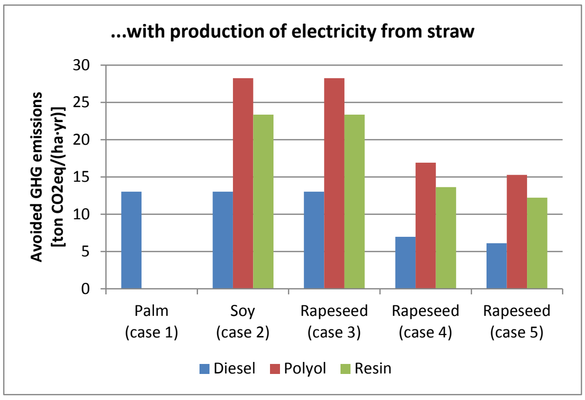


Figure 14b, …, fully developed biobased economy

Figure 12a and b show the GHG emissions for production of diesel, polyol and resin from different feedstocks (palm, soy, rapeseed and fossil). Polyol and resin cannot be produced from palm oil; therefore the respective bars are missing. Figure 13a and b show the GHG emissions that are avoided through production of biobased products compared to the fossil reference given in a and b. Figure 14 a and b show the GHG emissions that are avoided through biobased production per hectare of land needed to grow the biobased resources. Left graphs (a) show results for current practice; right graphs (b) show results for fully developed biobased economy scenario, where straw will be used for production of electricity.

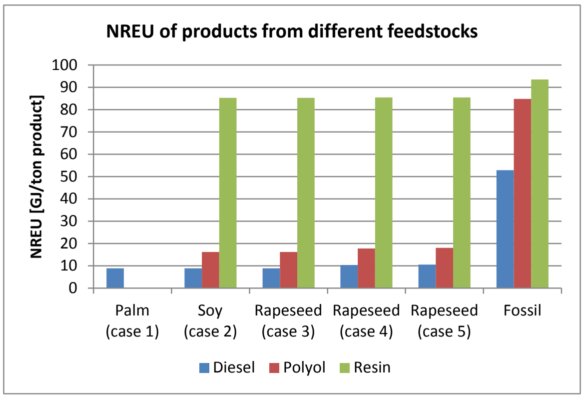


Figure 15a, NREU needed

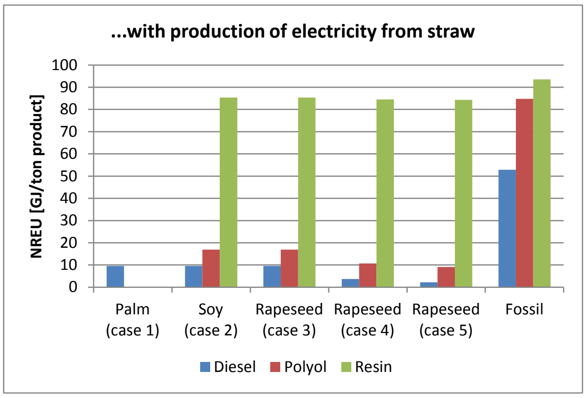


Figure 15b, …, fully developed biobased economy

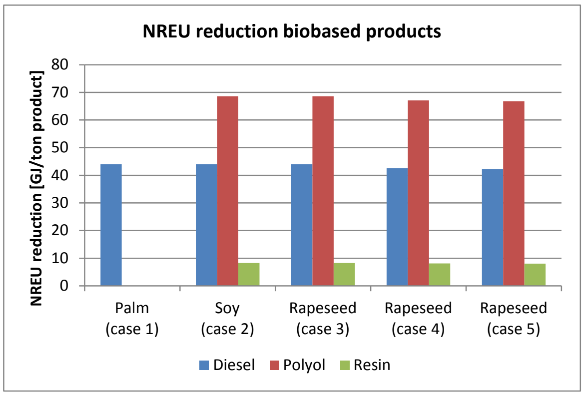


Figure 16a, NREU reduction compared to reference

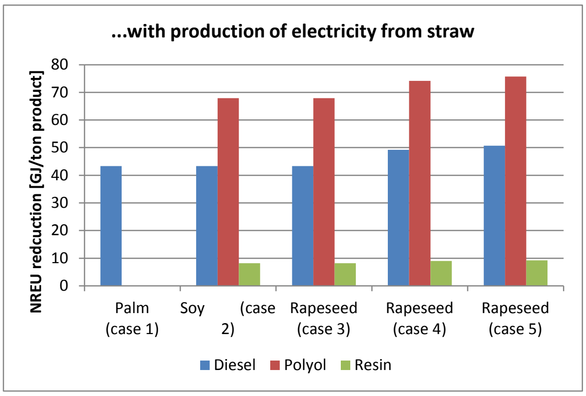


Figure 16b, …, fully developed biobased economy

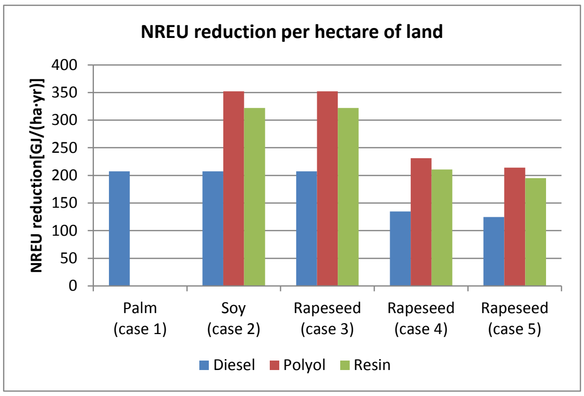


Figure 17a, NREU reduction per hectare per year

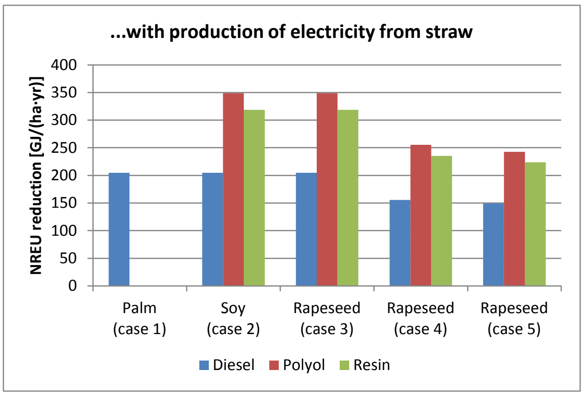


Figure 17b, …, fully developed biobased economy

Figure 15a and b show the Non Renewable Energy usage needed to produce diesel, polyol and resin from different feedstocks (palm, soy, rapeseed and fossil). Palm oil cannot be used to produce polyol or resin; therefore the respective bars are missing. Figure 16a and b show the NREU reduction achieved through the production of biobased products compared to the fossil based reference products given in Figure 15a and b. Figure 17a and b show the NREU reduction through biobased production per hectare of land needed to grow the biobased resources (vegetable oil). Left graphs (a) show results for current practice; right graphs (b) show results for fully developed biobased economy scenario, where straw will be used for production of electricity.

7 Conclusions

7.1 Production of vegetable oils (allocation via system expansion)

Through system expansion, the net NREU, the net GHG emission and the net land use of palm oil production (case 1) are equal to the figures for soy and rapeseed oil when replaced by increased palm oil production (case 2 and 3). If actual production of rapeseed oil is assumed (case 4 and case 5), GHG emissions will be considerably higher due to high N fertilizer usage during cultivation.

If electricity production from straw is included, the GHG emission for production of rapeseed oil (case 4 and 5) decreases. The production of rapeseed oil even becomes a net energy producing process (negative NREU). At the same time the results show a slight increase for palm, soy and rapeseed oil in case 1, 2 and 3. This is explained as follows: The use of soy or rapeseed oil will cause an increase of palm oil production. The accompanying production of palm kernel expeller will cause a small decrease of soybean and wheat production. Wheat and soybean have a coproduction of straw while oil palm is supposed not to have an increased utilization of biomass in the 'full BBE' scenario and therefore the total production of electricity will decrease.

7.2 Production of vegetable oils (comparison of allocation methods)

The present study has used system expansion as a default allocation method. The results were compared to other allocation methods (mass, energy and price based).

If system expansion is used, the NREU, GHG emissions and land use are equal for case 1, 2 and 3 in which palm oil is considered as marginal oil. This is not the case for the other allocation methods. In all cases, production of palm oil shows better results (lower NREU and lower GHG emission) than soy oil. Using system expansion, the NREU for rapeseed production (case 4 and case 5) is negative if electricity production from straw is assumed which is not the case for mass allocation.

Energy and economic allocation yield much higher NREU and GHG emission for production of soy and rapeseed oil than mass allocation.

If production of electricity from straw is assumed, the fundamental difference between system expansion and other accounting methods becomes evident. Using mass allocation, the NREU and GHG emission for soy oil production decreases. Using system expansion, the NREU and GHG emission for soy oil increases slightly. Similar issues are seen with GHG emissions and with rapeseed oil production (case 3). These issues illustrate that allocation methods cannot take market shifts into account and therefore the use of system expansion, despite its uncertainties, is to be preferred.

As shown in paragraph 6.1, the NREU for actual rapeseed production (case 4 and case 5) is negative if electricity production from straw is assumed. Mass allocation will not give negative results for production of the vegetable oil as the electricity is produced outside the system. It should be noted that the production of electricity from straw is an efficient way to reduce NREU, but it is also an expensive way. Costs were not included as an impact factor in the analysis, and therefore it must be kept in mind that the costs of different scenarios can be very different and that high costs might hinder realization of expensive scenarios (i.e. burning of straw for production of electricity as assumed in system allocation (line 5).

The effects of land use change (LUC) were not taken into account in this study. These effects can be considerable and should be further investigated (compare study of Laborde (2011) with 3 to 4 fold higher GHG emissions for palm and soy oil production.

7.3 Products from vegetable oils

All vegetable oil based product chains have lower NREU and GHG emissions than their fossil based reference.

NREU and GHG emission savings per ton of product decrease according to:
polyol > biodiesel > resin.

NREU and GHG emission savings per hectare decrease according to:
polyol > resin > biodiesel.

Thus, production of more complex products (making use of functionality of biobased resource) yields better NREU and GHG results than making fuels.

System expansion (case 1, 2 and 3) causes equal results for vegetable oil based products from palm, soy and rapeseed.

In case 4 and 5, rapeseed oil based products have considerably lower GHG emission reductions. The NREU reduction in case 4 and 5 is slightly lower than in case 1, 2 and 3 if current practice is assumed. If straw is used to produce electricity, the NREU reduction is higher for rapeseed oil based products (case 4 and 5). These differences are caused by differences occurring during oil production, during oil processing no differences between the oils occur.

The resin has only a very low biobased content. Therefore the avoided NREU and GHG emissions per ton of product are very low. If NREU and GHG emissions are expressed per hectare, the difference is much smaller and the production of resin performs better than production of biodiesel.

The reduction of NREU and GHG emissions of vegetable oil based products is comparable to sugar based products (reduction of NREU by approximately 300 GJ/ha and reduction of GHG emissions by approximately 20 ton/ha assuming current practice).

8 Recommendations

The effects of Land Use Change and Indirect Land Use Change (LUC and ILUC) were not taken into account in the present study. Even though these effects are still subject to considerable debate (Wicke *et al.*, 2012), it would be very worthwhile to get insight into the effects that LUC and ILUC might have on the conclusions of the present study.

It should be realised that currently production of electricity from straw is very expensive. This might (also in the future) hinder realization of the straw to energy scenario. It would be worthwhile to include economic impacts in the evaluation.

The NREU and GHG emission data of the resin per kg of product are very high. This is mainly caused by the large non-renewable fraction of this product. It would be interesting to calculate the NREU and GHG emission data per kg of renewable component.

The effects of usage of straw for production on electricity on the soil organic matter were not taken into account in the present study. It would be worthwhile to further investigate this issue on both GHG balance and soil fertility changes.

9 References

Arkansas Soybean Promotion Board, 2010, Arkansas Soybean Board Applaud's Ford's Use of Soy-based Foam in vehicles, http://www.themiraclebean.com/news/aspb-applauds-ford%E2%80%99s-use-soy-based-foam-vehicles

Ashland, 2011a, http://www.ketek.fi/anacompo/materials_kemi_january_2011/Tuula%20Mannermaa%20BIO-BASED%20ENVIREZ%20RESINS%20KEMI%2027012011.pdf

Ashland, 2011b, http://www.ashland.com/Ashland/Static/Documents/APM/PC-10065-NA_Envirez_Linecard%2001.27.10.pdf

BioGrace, 2010; 2011. Harmonised calculations of biofuel greenhouse gas emissions in Europe. Version 4. Accessible at: www.biograce.net.

Bos, H., K. Meesters, J.G. Conijn, W. Corré & M. Patel, 2010. Sustainability aspects of biobased applications. Comparison of different crops and products from the sugar platform. Report 1166. Food and Biobased Research, Wageningen, Nl.

Bos H., Conijn S., Corré W., Meesters K. and Patel M., 2011, Energiegebruik en broeikasgasemissie van producten met suikers als grondstof, ISBN 978-90-8585-902-4

Conijn, J.G. & W.J. Corré, 2009. Duurzaamheidaspecten van de teelt en verwerking van energiegewassen in Zuidoost Nederland. Rapport 261. Plant Research International, Wageningen, Nl.

Conijn, W.J. Corré, F.J. de Ruijter & B. Rutgers, 2011. Economic and environmental performance of oilseed cropping systems for biodiesel production. Report 418. Plant Research International. Nl.

Corley, R.H.V. & P.B. Tinker, 2003. The oil palm. Blackwell Science, Oxford, UK.

Corré, W.J. & J.G. Conijn, 2011. Parameterisation of E-CROP. Report. Plant Research International, Wageningen, Nl. (In preparation).

Dalgaard, R., J. Schmidt, N. Halberg, P. Christensen, M. Thrane & W.A. Pengue, 2008. LCA for food products. Case Study: LCA of soybean meal. International Journal of Life Cycle Assessment 13:240-254.

EC, 2009. Directive 2009/28/EC of the European Parliament and of the Council on the promotion of the use of energy from renewable sources. Official Journal of the European Union L 140. European Commission, Brussels, Be.

ECS, 2006-a. Environmental management – Life Cycle assessment – Principles and Framework. European Standard ISO 14040. European Committee for Standardisation, Brussels, Be.

ECS, 2006-b. Environmental management – Life Cycle assessment – Requirements and Guidelines. European Standard ISO 14044. European Committee for Standardisation, Brussels, Be.

FAOSTAT, 2011. Accessible at: www.faostat.fao.org

Hansen, S.B., Olsen, S.I., Islam, Z.U., 2012. Greenhouse gas reductions through enhanced use of residues in the Life Cycle of Malaysian palm oil derived biodiesel. Bioresource Technology 104: 358-366.

Hoefnagels R., E. Smeets, A. Faaij, 2010, Renewable and Sustainable Energy Reviews Volume 14, Issue 7, Pages 1661–1694

Laborde, D., 2011. Assessing the land use change consequences of european biofuel policies. Report IFPRI.

Lywood, W., J. Pinkney & S. Cockerill, 2009. Impact of protein concentrate coproducts on net land requirement for European biofuel production. GCB Bioenergy (2009) 1:346-359

Omni Tech International, 2010, Live Cycle Impact of Soybean Production and Soy Industrial Products

Pollack J., 2011, Personal communication

Reinhardt G.A., E. von Falkenstein, 2011, Environmental assessment of biofuels for transport and the aspects of land use Competition, biomass and bioenergy 35, 2315 - 2322

Reinhardt, J. & R. Zah, 2009. Global environmental consequences of increased biodiesel consumption in Switzerland: consequential life cycle assessment. Journal of Cleaner Production 17: 546-556.

Schmidt, J.H. & B.P. Weidema, 2008. Shift in the marginal supply of vegetable oil. International Journal of Life Cycle Assessment 13: 235-239

Weidema, B.P., 2001. Avoiding co-product allocation in Life-Cycle Assessment. Journal of Industrial Ecology 4-3: 11-33

Wicke B., Verweij P., Meijl H. van, Vuuren D.P. van, Faaij A.P.C., Indirect land use change: review of existing models and strategies for
Mitigation, Biofuels 3(1), 87-100, 2012.

Wikipedia, 2011a, http://en.wikipedia.org/wiki/Biodiesel

Wikipedia, 2011b, http://en.wikipedia.org/wiki/Soybean

Wikieducator,
2011, http://wikieducator.org/INDIFFERENCE_CURVES:_INCOME_EFFECT

10 Acknowledgements

The authors would like to thank Jim Pollack and his team at Omni Tech International for their kind help on the data.

Appendices

A.1. Compositions

Table 19, Carbon content of biomass components

Oil	80.6%
Protein	51.0%
Carbohydrate	44.4%

Table 20, Composition of soy beans (based on Wikipedia, 2011b)

	Total	**Organic**
Dry matter	94.68%	
Carbohydrates	30.16%	34.83%
Fat	19.94%	23.03%
Protein	36.49%	42.14%
Water	8.54%	
Ash	4.87%	
Total		**100.00%**

Table 21, Composition of soy beans (adjusted*)

	Total	**Dry matter**	**Organic**	**Total**	**Carbon content**
Water	20.0%			20.0%	
Dry matter	80.0%				
Ash		5.3%		4.2%	
Organic		94.7%			
Oil			25.0%	18.9%	15.3%
Protein			41.1%	31.1%	15.9%
Carbohydrate			33.9%	25.7%	11.4%
	100.0%	**100.0%**	**100.0%**	**100.0%**	**42.6%**

*with higher water and lower ash content to fit with carbon content as reported in Omni Tech International (2010), table 13

Table 22, composition of soy bean oil

	Total	Dry	Organic	Total	Carbon content
Water	4.5%			4.5%	
Dry matter	95.6%				
Ash		0.0%		0.0%	
Organic		100.0%			
Oil			100.0%	95.6%	77.0%
Protein			0.0%	0.0%	0.0%
Carbohydrate			0.0%	0.0%	0.0%
	100.0%	**100.0%**	**100.0%**	**100.0%**	**77.0%***

*fits with carbon content as reported in Omni Tech International (2010), table 13

Table 23, Composition of refined soy bean oil

	Total	Dry	Organic	Total	Carbon content
Water	0.0%			0.0%	
Dry matter	100.0%				
Ash		0.0%		0.0%	
Organic		100.0%			
Oil			100.0%	100.0%	80.6%
Protein			0.0%	0.0%	0.0%
Carbohydrate			0.0%	0.0%	0.0%
	100.0%	**100.0%**	**100.0%**	**100.0%**	**80.6%***

*fits with carbon content as reported in Omni Tech International (2010), table 13

Table 24, composition of soy bean meal

	Total	Dry	Organic	Total	Carbon content
Water	22.0%			22.0%	
Dry matter	78.0%				
Ash		6.9%		5.4%	
Organic		93.1%			
Oil			1.0%	0.7%	0.6%
Protein			54.2%	39.3%	20.1%
Carbohydrate			44.8%	32.5%	14.5%
	100.0%	**100.0%**	**100.0%**	**100.0%**	**35.1%***

*does not fit with carbon content as reported in Omni Tech International (2010), table 13

A.2. Process balances

Table 25, Production of soy bean oil from soy beans

	5236	1000	4131		Table 4
	SB	**SBO**	**SBM**	**diff.****	**Reference***
Water	1047.20	44.50	908.82	93.88	
Ash	222.01	0.00	223.75	-1.74	
Vegetable oil	991.70	955.50	29.98	6.21	
Protein	1628.83	0.00	1625.19	3.64	
Carbohydrate	1346.27	0.00	1343.26	3.01	
Total	**5236.00**	**1000.00**	**4131.00**	**105.00**	

*Reference to Omni Tech International report (2010)

**diff. shows the difference of inputs and outputs (should be zero)

Table 26, Soy bean oil refining

	1091	1000		
	SBO	**RSBO**	**Waste**	**Reference***
Water	48.53	0.00	48.53	
Ash	0.00	0.00	0.00	
Vegetable oil	1042.00	1000.00	42.00	Table 5
Protein	0.00	0.00	0.00	
Carbohydrate	0.00	0.00	0.00	
Total	**1090.53**	**1000.00**	**90.53**	

*Reference to Omni Tech International report (2010)

Table 27, Biodiesel production

	7.67		7.40			
	SBO	**Meth**	**BD**	**Glyc**	**Diff****	**Reference***
Water	0.34					
Vegetable oil	7.33					Table 6
FAME			7.40			Table 6
Methanol		0.77				Calc. from table 6
Glyc				0.89		Table 6
Total	**7.67**	**0.77**	**7.40**	**0.89**	**0.16**	

*Reference to Omni Tech International report (2010)

**diff. shows the difference of inputs and outputs (should be zero)

A.3. NREU and GHG emissions of soy bean oil refining

Table 28, NREU and GHG emissions from soy bean oil refining as derived from Omni Tech International (2010)

	NREU	Reference	NREU	GHG em.	NREU	GHG em.	NREU
Unit	BTU/1000kg		MJ/ton	kg/MJ	MJ/MJ	kg/ton	MJ/ton
Electrical energy	15223	Table 5	16.1	0.200	2.83	3	45
Steam energy	56644	Table 5	59.8	0.063	1.11	4	66
Sum			**75.8**			**7**	**112**

A.4. Calculations starting from Omni Tech Data

	SB from agr.				**SBO from agr.**				**RSBO from agr.**				**BD from agr.**				**SP from agr.**				**SR from agr.**		
GWP (incl. Incorp.)	-1200	kg/ton SB	Table 14		-2293				-2400	kg/ton RSBO	Table 16		-2100	kg/ton BD	Table 15		-1400	kg/ton SP	Table 17		4100	kg/ton SR	Table 18
NREU	1800	MJ/ton SB	Table 14		4048				4300	MJ/ton RSBO	Table 16		8700	MJ/ton BD	Table 15		16000	MJ/ton SP	Table 17		85200	MJ/ton SR	E-mail 11-11-11
CO2 Incorp.	1561	kg/ton SB	Page 10		2823	kg/ton SBO	Table 13		2955	kg/ton RSBO	Table 13		2823	kg/ton BD	Table 13		2689	kg/ton SP	Table 13		355	kg/ton SR	Table 13
	SB from agr.				**SBO from agr.**				**RSBO from agr.**				**BD from agr.**				**SP from agr.**				**SR from agr.**		
GWP (excl. Incorp.)	361	kg/ton SB			530	kg/ton SBO			555	kg/ton RSBO			723	kg/ton BD			1289	kg/ton SP			4455	kg/ton SR	
NREU	1800	MJ/ton SB			4048	MJ/ton SBO			4300	MJ/ton RSBO			8700	MJ/ton BD			16000	MJ/ton SP			85200	MJ/ton SR	
					SBO from SB				**RSBO from SBO**				**BD from SBO**				**SP from RSBO**				**SR from RSBO**		
alloc MP					19.50%	SBO	Table 4		99.30%	RSBO	Page 14		89%	BD	Page 17		100%	SP			100%	SR	
alloc SP					80.50%	SBM	Table 4		0.70%	Soap	Page 14		11%	glyc	Page 17								
Yield					0.190985	SBO/kgSB	Table 4		0.959693	kg RSBO/kg SB	Table 5		1.009701	kg BD/kg SBO	Table 6		1.098901	kg SP/kg RSBO	Table 13		8.333333	kg SR/kg RSBO	Table 13
	SB from agr.				**SBO from SB**				**RSBO from SBO**				**BD from SBO**				**SP from RSBO**				**SR from RSBO**		
GWP (excl. Incorp.)	361	kg/ton SB			161	kg/ton SBO	Table 5		7	kg/ton RSBO			256	kg/ton BD			784	kg/ton SP			4388	kg/ton SR	
NREU	1800	MJ/ton SB			2210	MJ/ton SBO	Table 5		112	MJ/ton RSBO			5132	MJ/ton BD			12087	MJ/ton SP			84684	MJ/ton SR	

A.5. Calculations starting from WUR-PRI data (current practice)

Case 1, 2 and 3

	Veg. oil from agr.		Ref. veg. oil from agr.		BD from agr.		Polyol from agr.		Resin from agr.	
GHG incl. Incorp	500	kg/ton veg. oil	524	kg/ton ref. veg. oil	697	kg/ton BD	1261	kg/ton polyol	4451	kg/ton resin
NREU	4300	MJ/ton veg. oil	4561	MJ/ton ref. veg. oil	8922	MJ/ton BD	16237	MJ/ton polyol	85231	MJ/ton resin
Landuse		ha/ton veg. oil	0.214	ha/ton ref. veg. oil	0.212	ha/ton BD	0.195	ha/ton polyol	0.026	ha/ton resin
GHG incl. Incorp	-2323	kg/ton veg. oil	-2431	kg/ton ref. veg. oil	-2126	kg/ton BD	-1428	kg/ton polyol	4096	kg/ton resin

Case 4

	Veg. oil from agr.		Ref. veg. oil from agr.		BD from agr.		Polyol from agr.		Resin from agr.	
GHG incl. Incorp	1440	kg/ton veg. oil	1497	kg/ton ref. veg. oil	1525	kg/ton BD	2146	kg/ton polyol	4568	kg/ton resin
NREU	5900	MJ/ton veg. oil	6216	MJ/ton ref. veg. oil	10332	MJ/ton BD	17744	MJ/ton polyol	85430	MJ/ton resin
Landuse		ha/ton veg. oil	0.319	ha/ton ref. veg. oil	0.316	ha/ton BD	0.290	ha/ton polyol	0.038	ha/ton resin
GHG incl. Incorp	-1383	kg/ton veg. oil	-1458	kg/ton ref. veg. oil	-1298	kg/ton BD	-543	kg/ton polyol	4213	kg/ton resin

Case 5

	Veg. oil from agr.		Ref. veg. oil from agr.		BD from agr.		Polyol from agr.		Resin from agr.	
GHG incl. Incorp	1670	kg/ton veg. oil	1735	kg/ton ref. veg. oil	1728	kg/ton BD	2362	kg/ton polyol	4597	kg/ton resin
NREU	6200	MJ/ton veg. oil	6527	MJ/ton ref. veg. oil	10597	MJ/ton BD	18026	MJ/ton polyol	85467	MJ/ton resin
Landuse		ha/ton veg. oil	0.343	ha/ton ref. veg. oil	0.340	ha/ton BD	0.312	ha/ton polyol	0.041	ha/ton resin
GHG incl. Incorp	-1153	kg/ton veg. oil	-1220	kg/ton ref. veg. oil	-1095	kg/ton BD	-327	kg/ton polyol	4242	kg/ton resin

A.6. Calculations starting from WUR-PRI data (straw for energy)

Case 1, 2, 3

	Veg. oil from agr.		**Ref. veg. oil from agr.**		**BD from agr.**		**Polyol from agr.**		**Resin from agr.**	
GHG	530	kg/ton SBO	555	kg/ton RSBO	723	kg/ton BD	1289	kg/ton SP	4455	kg/ton SR
NREU	5000	MJ/ton SBO	5285	MJ/ton RSBO	9539	MJ/ton BD	16896	MJ/ton SP	85318	MJ/ton SR
GHG incl. Incorp	-2293	kg/ton SBO	-2400	kg/ton RSBO	-2100	kg/ton BD	-1400	kg/ton SP	4100	kg/ton SR

Case 4

	Veg. oil from agr.		**Ref. veg. oil from agr.**		**BD from agr.**		**Polyol from agr.**		**Resin from agr.**	
GHG	1160	kg/ton SBO	1207	kg/ton RRSO	1278	kg/ton BD	1882	kg/ton SP	4533	kg/ton SR
NREU	-1600	MJ/ton SBO	-1544	MJ/ton RRSO	3722	MJ/ton BD	10682	MJ/ton SP	84499	MJ/ton SR
GWP incl. Incorp	-1663	kg/ton SBO	-1748.14	kg/ton RRSO	-1545	kg/ton BD	-807	kg/ton SP	4178	kg/ton SR

Case 5

	Veg. oil from agr.		**Ref. veg. oil from agr.**		**BD from agr.**		**Polyol from agr.**		**Resin from agr.**	
GHG	1310	kg/ton SBO	1362	kg/ton RRSO	1411	kg/ton BD	2023	kg/ton SP	4552	kg/ton SR
NREU	-3300	MJ/ton SBO	-3303	MJ/ton RRSO	2223	MJ/ton BD	9081	MJ/ton SP	84288	MJ/ton SR
GWP incl. Incorp	-1513	kg/ton SBO	-1592.93	kg/ton RRSO	-1412	kg/ton BD	-666	kg/ton SP	4197	kg/ton SR

A.7. Units and Abbreviations

Table 29, Units

Unit	Explanation
GJ	Giga Joule (=10^9 Joule)
ha	Hectare (=10000 m^2)
MJ	Mega Joule (=10^6 Joule)
Mt	Mega ton (= 10^9 kilogram)

Table 30, Abbreviations

Abbreviation	Explanation
BBE	BioBased Economy
BBT	Process to produce polyols by company BBT
BD	Biodiesel
CHP	Combined Heat and Power
CO_2eq	Carbon Dioxide Equivalent
diff	Difference
Em.	Emission
FAME	Fatty Acid Methyl Ester
GHG	Green House Gas
Glyc	Glycerol
GWP	Global Warming Potential
ISO	International Organization for Standardization
Meth	Methanol
NREU	Non Renewable Energy Usage
RED	Renewable Energy Directive
RRSO	Refined RapeSeed Oil
RSBO	Refined Soy Bean Oil
SBM	Soy Bean Meal
SBO	Soy Bean Oil
SBOR1	Soy Bean Oil Refinery 1
SBOR2	Soy Bean Oil Refinery 2
SP	Soy Polyol
SR	Soy Resin
Trans.	Transesterification process
Veg.	Vegetable
Ref.	Refined

B.1. Appendix: additional electricity production of oil palm side products

In the ‘full BbE’ scenario as presented in chapter 3 no additional electricity production from oil palm crop residues compared with the ‘current practice’ scenario was considered due to a lack of demand for electricity in the palm oil producing regions in South-East Asia. However, also the demand for electricity produced from straw in soybean producing regions in Brazil is doubtful but has been calculated in section 3.5. For an exploration of the potentials of a fully developed Biobased Economy on a level playing field, this Appendix contains the results of the ‘full BbE’ scenario, including electricity production from oil palm crop residues.

The production of palm oil delivers a large amount of co-products of which only a small part is currently used. Palm kernel expeller (PKE, meal of the palm kernel) is used as feed and the (mesocarp) fibres and the larger part of the kernel shells are used for the production of energy in the oil mill. A minor part of the kernel shells are sold as fuel but due to a lack of demand for biomass the energy used in the palm oil mills is generated inefficiently and much crop residues remain unutilised. A very small part of the fronds are used as feed and a very small part of the trunks is used for wood products but both co-products have a low quality for these purposes. Potential sources of energy are quantified in Table 28 and an adapted flow chart is presented in Figure 19, to be compared with Figure 3.

Table 28, Co-products available from the production of palm oil.

Co-products	Current use	Production (ha^{-1} yr^{-1})	Source
Meal (PKE)	feed	0.47 ton d.m.	Hansen et al., 2012
Biogas from waste water (POME) treatment	captured and flared	212 m^3 methane	Vijaya et al., 2008
Empty fruit bunches	returned to	1.44 ton d.m.	Hansen et al., 2012
Fibres	plantation	1.54 ton d.m.	Ibid.
Kernel shells	internal use	1.15 ton d.m.	Ibid.
Fronds, annually pruned	internal use	10.4 ton d.m.	Chan et al., 1980
plantation	left in field	0.58 ton d.m.	Ibid.[a]
renewal	left in field	2.8 ton d.m.	[b]
Trunks, plantation renewal	left in field		

[a]: 14.4 ton dry matter in a 25 year old plantation.

[b]: average of 75.5 ton dry matter in a 30 year old plantation (Chan et al., 1980) and 70 ton dry matter in a 23 year old plantation (Kee, 2004).

For the scenario ‘current practise’ the internal use of energy in the palm oil mill is supposed to be produced from the fibres and part of the kernel shells, fronds and trunks are left in the field, the empty fruit bunches (EFB) are returned to the field as mulch or compost and the biogas from waste water treatment (POME; palm oil mill effluent) is captured and flared. In the ‘full BbE’ scenario a surplus electricity is produced and loaded to the grid. This electricity is produced from the biogas, the trunks and fronds and the surplus kernel shells, which is estimated at 0.875 ton dry matter ha^{-1} yr^{-1} when the efficiency of the energy production from fibres and shells in the palm oil mill is optimised. In theory, the electricity production could be enlarged by using EFB and PKE but regarding the large production of electricity, recycling of nutrients and carbon from EFB and using protein rich PKE as feed seems more useful. The heat produced as co-product of electricity is not used, except for drying of the fronds which have a moisture content of 60% (Ruslan et al., 2011) and the trunks which have a moisture content of 75% (Mori, 2007) and for keeping the temperature of the waste water digestion reactors at an optimal level.

Capturing of biogas from the POME treatment is only partly current practice, in the majority of palm oil mills the methane from POME treatment is still emitted to the atmosphere. The emitted quantity of methane is uncertain: BioGrace (2012) considers an emission of circa 2000 kg CO_2-eq of methane ha^{-1} yr^{-1} and Yacob et al. (2006) measured an emission of almost 4000 kg CO_2-eq of methane ha^{-1} yr^{-1}. In this latter case the emission seemed higher than average (Hansen et al., 2012) due to a very long retention time of the POME in anaerobic lagoons, but it is clear that biogas capture (with or without utilisation for energy production) is an important issue in the CO_2 footprint of palm oil production.

The difference between the scenario with electricity production from straw as described in chapter 3 of this report and the ‘full BbE’ scenario as described in this appendix is an increased utilisation of oil palm crop residues for the production of electricity by utilising the captured biogas from POME treatment, the surplus kernel shells, the fronds from pruning and plantation renewal and the palm trunks from plantation renewal. The results of the calculations of energy use, greenhouse gas emission and land use from this adapted scenario are presented in Table 29 to 31, comparable with Table 4, 6 and 7 for the original scenario.

The most obvious difference between the results in this appendix and the results in Chapter 3 is the large decrease in NREU and GHG emission from the production of palm oil, due to the large amount of electricity that is generated from oil palm crop residues. The decrease of NREU and GHG emission is clearly larger for palm oil than for rapeseed oil and results not only a net energy production but also a negative GHG emission from oil production. Due to the interaction with palm oil production, utilising oil palm crop residues leads also to a decrease of the NREU and GHG emission of rapeseed oil production.

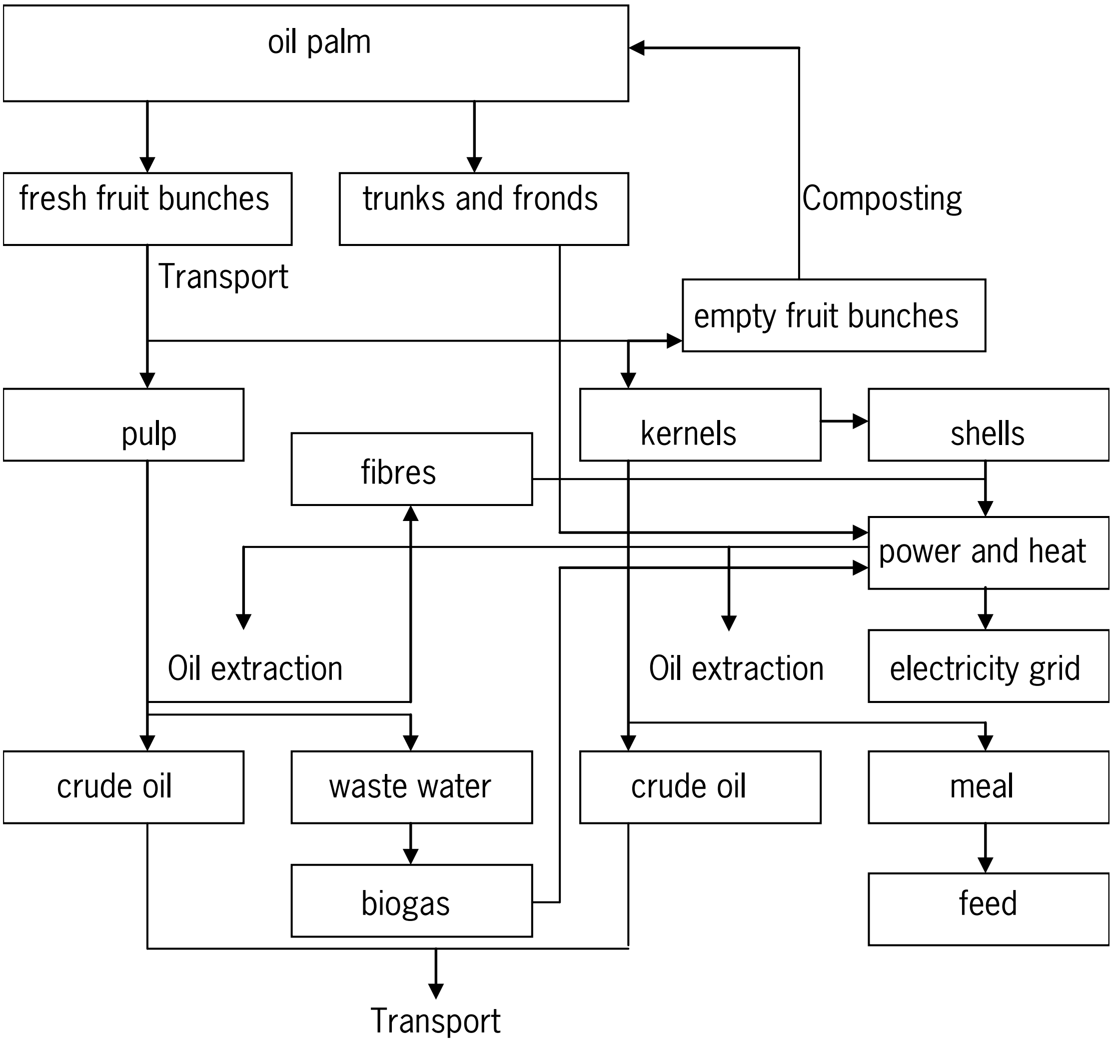


Figure 19, Flow chart for the production of vegetable oil from oil palm, including utilisation of crop residues.

The comparison of methods of accounting for co-products as presented in Table 13 and 14 is adapted to the use of oil palm crop residues and presented in Table 33 and 34. The new calculations resulted in more negative values for system expansion, with as result larger differences with allocation methods which can principally not have negative values as result. The removal of crop residues for combustion implies the removal of nutrients, which should be compensated for by an increased application of fertilisers. For straw, this compensation is neglected because nitrogen in straw is supposed to be used by a following crop with a low efficiency (De Haan & Van Geel, 2013). For oil palm, however, the utilisation of nitrogen from crop residues is much more efficient. Under current practice the nitrogen surplus (fertiliser application minus removal in fresh fruit bunches) is circa 50 kg N ha^{-1} yr^{-1}, while pruned fronds contain circa 100 kg N ha^{-1} yr^{-1}. This difference in use efficiency is probably caused by the nature of the crop; in a continuously growing tropical perennial crop the timing of nitrogen mineralisation will correspond much better with the timing of plant uptake. This implies that compensation of nutrient removal is necessary. Because the efficiency with which the nutrients recycled with pruned fronts is not known, we have chosen for a complete compensation. The nutrients in trunks and fronds recycled at plantation renewal are supposed to be used much less efficient due to the absence of a developed crop after the renewal and compensation of the removal is neglected. Nutrients in the surplus kernel shells are already removed under current practise and will be taken into account in the current fertilisation. Extra fertilisation to compensate for the extra nutrient removal (109 kg N, 23 kg P_2O_5 and 160 kg K_2O ha^{-1} yr^{-1}) has a clear effect: it causes a NREU of 6.4 GJ ha^{-1} yr^{-1} and a GHG emission of 1850 kg CO_2-eq ha^{-1} yr^{-1}. Complete compensation of nutrient removal with straw of soybean or rapeseed would cause a NREU of circa 1 GJ ha^{-1} yr^{-1} and a GHG emission of circa 300 kg CO_2-eq ha^{-1} yr^{-1}.

Using oil palm crop residues for electricity production in a full BbE scenario has a negative effect on soil C sequestration, however this effect has not been estimated in this study. Therefore the value for net GHG emission as presented in this report is overestimated, but the estimation of the magnitude of this effect still needs further study.

In this Appendix the potential electricity production, for oil palm (and soybean) is calculated but would lead to regional overproduction of electricity in the current situation. Even for straw in Western Europe, where the market could absorb the produced electricity, this electricity production is not developed. Only in Denmark an appreciable part of the produced straw is currently used for energy production due to political pressure. The results of this Appendix, however, give a good illustration of possible effects of a further development of the Biobased Economy by increased use of crop residues.

Table 29, *Input and substitution data for the calculation of energy input, GHG emission and land use in the production of vegetable oil.*

	Unit	Palm S-E Asia	Soy bean Brazil	Rapeseed Europe	Wheat Europe
Yield (fresh matter)	ton ha^{-1} yr^{-1}	19.00	2.80	3.55	7.20
Dry matter product.	ton ha^{-1} yr^{-1}	12.54	2.38	3.20	6.26
Crude oil contents	% of d.m.	34.4	22	45.5	--
Crude oil yield	ton ha^{-1} yr^{-1}	4.31	0.52	1.46	--
Crop residues (fresh)	ton ha^{-1} yr^{-1}	39.5[a]	2.50	2.50	4.00
Crop residues d.m.	ton ha^{-1} yr^{-1}	14.7	2.13	2.13	3.40
Biogas	m^3 CH$_4$ ha^{-1} yr^{-1}	212			
Transport distance	km truck	20[b]	1100[d]	100[d]	100[d]
	km truck	150[c]			
	km train	0	600[d]	500[d]	500[d]
	km ship	10000[c]	10000[d]		
	km truck	50[g]	50[g]	50[g]	50[g]
Meal production (d.m.)	ton ha^{-1} yr^{-1}	0.47	1.86	1.74	--
Soy meal replaced fresh	ton ha^{-1} yr^{-1}	0.06		1.04	--
Wheat replaced fresh	ton ha^{-1} yr^{-1}	0.30		0.26	--
Palm oil produced[e]	ton ha^{-1} yr^{-1}	0.017		0.29	--
Electricity	GJ ha^{-1}	77.1	10.8	10.8	17.3
Heat[f]	GJ ha^{-1}	124.3	18.1	18.1	28.9

[a]: Surplus kernel shells, fronds and trunks.
[b]: Fresh fruit bunches.
[c]: Crude oil only.
[d]: Seeds.
[e]: Produced to replace the soy oil not produced due to replacing soy meal.
[f]: Heat is presumed not to be utilised externally, only for drying crop residues.
[g]: Crop residues.

For figures on energy input, GHG emission and land use in the production of vegetable oil according to current agricultural practices, see Table 5.

Table 30, *Energy input, GHG emission and land use in the production of vegetable oil: effects of electricity production from crop residues.*

	Unit	Palm S-E Asia	Soy bean Brazil	Rapeseed Europe	Wheat Europe
Energy input					
NREU residues[a]	GJ ha^{-1}	37.8	3.0	3.0	4.1
Electricity prod.	*GJ ha^{-1}*	*-77.1*	*-10.8*	*-10.8*	*-17.3*
Electricity credit[b]	GJ ha^{-1}	-230.6	-32.4	-32.4	-51.8
NREU indirect[c]	GJ ha^{-1}	2.5		5.5	--
NREU total.	GJ ha^{-1}	-190.3		-23.9	-47.4
	GJ ton^{-1} oil	*-44.1*		*-16.4*	--
GHG emission					
GHG residues[a]	kg CO_2-eq. ha^{-1}	3730	75	100	110
El. prod. em. red	kg CO_2-eq. ha^{-1}	-8950	-1260	-1260	-2010
GHG indirect[c]	kg CO_2-eq. ha^{-1}	110		390	--
GHG emission	kg CO_2-eq. ha^{-1}	-5110		-770	-1900
total	*kg CO_2-eq. ton^{-1} oil*	*-1190*		*-530*	--

[a]: Collecting, transport, processing, avoided emission from crop residue input and compensation of removed nutrients.

[b]: Efficiency of alternative electricity production is assumed 2.99 MJ MJ^{-1}_{el} and 116 g CO_2-eq MJ^{-1}.

[c]: NREU/GHG indirect: net electricity credit or net GHG emission reduction from straw of soy bean and wheat that are replaced due to the extra meal production as result of the increased oil production.

Table 31, *Energy input, GHG emission and land use in the production of vegetable oil, including electricity production from crop residues.*

	Unit	Case 1,2,3	Case 4
Energy input			
Current practice	GJ ha^{-1}	18.5	8.5
Electricity residues	GJ ha^{-1}	-190.3	-23.9
Total	GJ ha^{-1}	-171.8	-15.4
Total	*GJ ton^{-1} oil*	*-39.8*	*-10.6*
GHG emission			
Current practice	kg CO_2-eq. ha^{-1}	2170	2090
Electricity residues	kg CO_2-eq. ha^{-1}	-5110	-770
Total	kg CO_2-eq. ha^{-1}	-2940	1320
Total	*kg CO_2-eq. ton^{-1} oil*	*-680*	*910*

Table 33, GHG emission of vegetable oil production (ton CO_2eq/ton oil), corrections and additions to Table 13 for the scenario with energy production from crop residues.

Line	Electricity	Accounting	Base	Allocation over	Palm	Soy	Soy (OTI)	Rapeseed
5	yes	syst. exp.			-0.68[a]	-0.66[b]		-0.66[b]/0.92[c]
6	yes	allocation	mass	oil, meal and co-pr.	0.21	0.48		0.59
7	yes	allocation	energy	oil, meal and co-pr.	0.27	0.81		0.90

[a]: in system expansion palm oil is produced (case 1)

[b]: in system expansion soy oil (case 2) and rapeseed oil (case 3) are replaced by palm oil (hence equal results)

[c]: in system expansion rapeseed oil is actually produced (case 4)

Table 34, NREU of vegetable oil production (GJ/ton oil), corrections and additions to Table 14 for the scenario with energy production from crop residues.

Line	Electricity	Accounting	Base	Allocation over	Palm	Soy	Soy (OTI)	Rapeseed
5	yes	syst. exp.			-39.8[a]	-39.8[b]		-39.8/-10.6[c]
6	yes	allocation	mass	oil, meal and co-pr.	2.1	5.8		3.9
7	yes	allocation	energy	oil, meal and co-pr.	2.6	9.7		5.8

[a]: in system expansion palm oil is produced (case 1)

[b]: in system expansion soy oil (case 2) and rapeseed oil (case 3) are replaced by palm oil (hence equal results)

[c]: in system expansion rapeseed oil is actually produced (case 4)

References

BioGrace, 2011. Harmonised calculations of biofuel greenhouse gas emissions in Europe. Version 4. Accessible at: www.biograce.net.

Chan, K.W., Watson, I.A., Lim, K.C., 1980. Use of oil palm waste material for increased production. In: E. Pushparajah and S. C. Chin, eds. Soil Science and Agriculture Development in Malaysia, pp. 213–242.

De Haan, J.J., Van Geel, W., 2013. Adviesbasis voor de bemesting van akkerbouwgewassen – Stikstof. Accessible at: www.kennisakker.nl.

Hansen, S.B., Olsen, S.I., Ujang, Z., 2012. Greenhouse gas reductions through enhanced use of residues in the Life Cycle of Malaysian palm oil derived biodiesel. Bioresource Technology 104: 358-366.

Kee, K-K., 2004. Nutrient reserves and recycling from oil palm trunks at replanting. Proceedings of the 4th International Crop Science Congress, Brisbane, Australia, 26 Sep - 1 Oct 2004.

Mori, Y., 2007. Old oil palm trunks as promising feedstock for biofuel and bioplastics. *http://www.unep.or.jp/ietc/spc/news-mar10/0304_1130_OldOilPalmTrunksAsPromisingFeedstockForBiofuel&Bioplastics(JIRCAS).pdf*

Ruslan, M.H., Fudholi, A., Othman, Y., Azmi, M.S.M., Yahia, M., Zaharim, A., Sopian, K., 2011. The Double-Pass Solar Dryer for drying palm oil fronds. Proceedings of the 11th WSEAS/IASME International Conference on Electric Power Systems, High Voltages, Electric Machines and the 10th WSEAS International Conference on System Science and Simulation in Engineering. Pp 143-149.

Vijaya, S., Ma, S.N., Choo, M.Y., Nik Meriam, N.S., 2008. Life Cycle Inventory of the production of crude palm oil – a gate to gate study of 12 palm mills. Journal of Oil Palm Research 20: 484-494.

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