**Comparison of the Greenhouse Gas Benefits Resulting from Use of Vegetable Oils for Electricity, Heat, Transport and Industrial Purposes**

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## Executive Summary

This report documents the findings of a study into a comparison of the greenhouse gas (GHG) emissions benefits resulting from the use of vegetable oils for electricity, heat, transport and industrial purposes. The study was commissioned by the Department of Energy and Climate Change, managed by the National Non-Food Crops Centre and conducted by North Energy Associates Ltd. The aims of this study were to evaluate and compare the total GHG emissions associated with the production of refined vegetable oils derived from a range of specified biomass feedstocks and their subsequent use, either as oils or derived biodiesel, in a range of end-use applications. The specified biomass feedstocks consist of:

- Used cooking oil available in the United Kingdom (UK),
- Oilseed rape cultivated in the UK,
- Soy beans cultivated in the United States of America (USA),
- Sunflowers cultivated in France,
- Oil palms cultivated in Malaysia, and
- Jatropha cultivated in India.

The specified end-use applications consist of:

- Refined vegetable oil used for electricity (only) and combined heat and power generation,
- Biodiesel used for heat (only), electricity (only) and combined heat and power (CHP) generation, and transport fuel, and
- Biolubricant.

Compliance with the current calculation methodology described by the European Commission Renewable Energy Directive (EC RED) was required although other calculation methodologies, including the current Renewable Fuels Agency (RFA) Technical Guidance, the British Standards Institution Publicly-Accessible Standard (PAS) 2050 and the Biomass Environmental Assessment Tool ($BEAT_2$) are also considered. In addition to the preparation of basic results on total GHG emissions (and primary energy inputs), it was necessary to conduct sensitivity analysis to determine any major factors that might influence the comparison of results.

Given the scope of this study and the need to examine the possible effect of a number of different variable and assumptions, a series of MS Excel workbooks were developed to represent the biomass feedstocks and end-use applications to be considered. These workbooks are based on an approach and structure that has been adopted by North Energy in previous work on biomass energy technologies, renewable chemicals and biomaterials. The workbooks are fully transparent, recording all calculations, sources of data and assumptions, and suitably functional to address all the relevant issues. The workbooks produced results in different forms and include the evaluation of net GHG emissions savings for vegetable oils, their derivative products and end-use applications relative to conventional fossil fuel-derived products and services, in terms of net GHG emissions savings.

On this basis, following main conclusions were made in this study:

Total net GHG emissions savings (ranging from 18% to 100%) are possible for using UK used cooking oil, in all end-use applications, in place of all the conventional fossil fuel-based alternatives considered in the study. Total net GHG emissions savings (ranging from 3% to 76%) are also possible with all the other biomass feedstocks (derived from cultivated crops) considered in this study apart from:

- Using refined vegetable oil from UK oilseed rape, US soy beans, Malaysian oil palms and India jatropha to generate electricity instead of using natural gas (total net GHG emissions savings of – 35%, -50%, - 8% and -67%, respectively).
- Using refined vegetable oil from US soy beans and Indian jatropha to generate electricity instead of using UK grid electricity (total net GHG emissions savings of – 6% and – 18%, respectively).
- Using biodiesel from US soy beans and Indian jatropha in CHP generation instead of natural gas-fired CHP generation (total net GHG emissions savings of – 5% and – 23%, respectively).
- Using biodiesel from UK oilseed rape, US soy beans, French sunflowers, Malaysian oil palms and Indian jatropha to generate electricity instead of using natural gas (total net GHG emissions savings of – 59%, - 95%, - 27%, - 37% and – 109%, respectively).
- Using biodiesel from US soy beans and Indian jatropha to generate electricity instead of using fuel oil (total net GHG emissions savings of – 10% and – 18%, respectively).
- Using biodiesel from UK oilseed rape, US soy beans and Indian jatropha to generate electricity instead of using UK grid electricity (total GHG emissions savings of – 12%, - 37% and – 47%, respectively).

Total net GHG emissions savings can be maximised by using any of the refined vegetable oils considered in this study in CHP generation instead of fuel oil-fired heat and UK grid electricity (ranging from 47% to 100%), or by using biodiesel to generate heat instead of using fuel oil (ranging from 36% to 83%). Total net GHG emissions savings from using biodiesel in heat applications which replace fuel oil-fired heating (ranging from 36% to 83%) are marginally higher than those savings from using biodiesel as a transport fuel to displace diesel derived from conventional crude oil (ranging from 25% to 82%). However, total net GHG emissions savings from biodiesel used in transport are marginally higher than those for its use in heat applications which displace natural gas (ranging from 13% to 77%) and CHP applications which displace natural gas heat production and grid electricity (ranging from 14% to 79%). Total net GHG emissions savings from transport biodiesel are significantly higher than those when biodiesel is used on CHP applications which displace natural gas CHP (ranging from – 23% to 70%). In general, of all the cultivated biomass feedstocks considered in this study, the highest total net GHG emissions savings arise from the use of French sunflowers and Malaysian oil palms.

Net savings for UK used cooking oil are relatively insensitive to road transport distances involved in collecting this biomass feedstock. Irrigation during cultivation is an important consideration which affects the net savings (negatively) for US soy beans and Indian jatropha. Switching from the use of CHP units in processing to fossil fuel-fired heat (only) boilers and national grid electricity affects the net savings (negatively) for UK oilseed rape, French sunflowers and Malaysian oil palms (slightly), and for US soy beans and Indian jatropha (moderately). Net savings for Malaysian oil palms are most sensitive (positively) to the capture and flaring of methane from palm oil mill effluent.

The choice of methodologies for GHG emissions calculations hardly affects the net savings for UK cooking oil. Each of the other biomass feedstocks is affected differently by application of different official methodologies for GHG emissions calculations in these specific cases considered here. For UK oilseed rape, the highest savings are estimated using the EC RED methodology, followed by the RFA methodology, with lowest savings from the PAS 2050 and $BEAT_2$ methodologies which are similar. Relatively similar savings are derived for UK soy beans regardless of the choice of official methodology. The highest savings from French sunflowers are with the EC RED methodology which produces similar results to the RFA methodology whilst the lowest savings are with the PAS 2050 and $BEAT_2$ methodologies. Savings from Malaysian oil palms are similar for all the relevant official methodologies with the highest, marginally, being with the EC RED methodology over the PAS 2050 and $BEAT_2$ methodologies. However, there are significant differences in the savings for jatropha, with the highest savings which are estimated with the EC RED methodology contrasting markedly with very small or negative savings (lowest) from the PAS 2050 and $BEAT_2$ methodologies which produce similar results.

Total net primary energy savings, as a measure of avoided energy resource depletion, are demonstrated for all biomass feedstocks and end-use applications (ranging from 9% to 100%) apart from using biodiesel from US soy beans and Indian jatropha to generate electricity instead of natural gas (total net primary energy savings of – 22% and -11%, respectively).

Amongst all the biomass feedstocks considered in this study, only biolubricants derived from UK used cooking oil are capable of reducing total GHG emissions relative to motor oil derived from conventional crude oil, although this depends, critically, on the fate of losses during use and the chosen waste disposal method. The highest net savings are possible if all the biolubricant is lost and all contained carbon is sequestered. Next highest net savings can be achieved if all of the biolubricant is recovered and incinerated with energy recovery. Higher total GHG emissions than those for conventional motor oil occur if all the biolubricant is lost during use and contained carbon is eventually converted to carbon dioxide or, in the very considerably worst case, methane. Unfortunately, the actual fate of carbon contained in lost biolubricant cannot be specified in this study due to a lack of robust scientific evidence.

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# 1 INTRODUCTION

## 1.1 Background

Vegetable oils can be derived from a diverse range of biomass feedstocks, and processed, in addition to their traditional use in food preparation and cosmetics, for the production of energy, in general, and transport fuels, in particular. Refined vegetable oil and biodiesel, collectively, are included with other liquid and gaseous fuels obtained from biomass under the term of “biofuels”. The potential attraction of these biofuels is that, as they are derived, originally, from organic matter, any carbon dioxide ($CO_2$) emitted during combustion is balanced by the $CO_2$ which they absorbed from the atmosphere during growth. It is, however, widely recognised and appreciated that emission of $CO_2$ and other greenhouse gases (GHGs), such as methane ($CH_4$) and nitrous oxide ($N_2O$), arise from the cultivation, harvesting, transportation of biomass feedstocks and their subsequent processing and distribution as biofuels. As other studies on liquid biofuels have demonstrated, such GHG emissions can be significant, depending on the type of biomass feedstock and the details of conversion into a suitable biofuel.

The evaluation of GHG emissions associated with biofuel production is conducted within the context of life cycle assessment (LCA). Most LCA work on biofuels has focused on the production of alternatives, such as biodiesel, to conventional transport fuels derived from fossil fuels, specifically crude oil. Whilst there are many reasons for this specific focus, policy measures which promote the production and use of transport biofuels are centrally important. The emphasis placed on global climate change mitigation in these policies underpins the need to establish the GHG emissions savings of biofuels relative to conventional transport fuels. However, GHG emissions savings can also be achieved by using these biofuels (such as biodiesel) and their precursors (such as refined vegetable oil) in other applications. In particular, biofuels can be used to generate heat and/or electricity. Additionally, vegetable oils can be converted into biolubricants as alternatives to fossil fuel-derived lubricants. The relative GHG emissions savings which might be realised by these different possible uses of vegetable oils can be established through LCA.

## 1.2 Aims and Objectives

The aims of this study have been to evaluate and compare the total GHG emissions associated with the production of a specified range of vegetable oils (from used cooking oil, oilseed rape, soy beans, sunflowers, oil palm and jatropha) and their subsequent use, either as oils or derived biodiesel, in a range of end-use applications (refined oil for electricity generation and combined heat and power generation, biolubricant, and biodiesel for heat, electricity and combined heat and power generation, and transport fuel). The objectives required suitable results to be estimated in the form of kilograms of equivalent[1] $CO_2$ per unit of energy (MJ) or relevant product output and in terms of GHG emissions savings relative to fossil alternatives. The details of GHG emissions calculations depend on the adopted methodology, of which there are various choices. However, in this instance, consistency with the methodology in the current version of

[1] Conversion to aggregated units of GHG emissions being achieved through the use of Global Warming Potentials (GWPs) for $CH_4$ and $N_2O$ relative to $CO_2$.

the Renewable Energy Directive (EC RED) of the European Commission (EC, 2009) was of primary importance. Where necessary, this methodology has to be extended using reasonable assumptions, from its current application with biofuels to heat, electricity, combined heat and power, and biolubricants. A modelling approach was required which will enable the effect of key parameters on results to be explored. Consequently, the study involved the preparation of MS Excel workbooks following established practice by North Energy Associates Ltd.

### 1.3 Structure of Report

Although 6 relevant workbooks are key deliverables, it is the main results derived from their use in this study that are reported here. The derivation of these results must be set within the context of methodologies for calculating GHG emissions. The pertinent features of such methodologies, as they apply to vegetable oil production and use, are explained in Section 2. The main features of the workbooks, including important aspects of the significant user variables and the default value settings for the so-called "base cases" are summarised in Section 3. Major results are reported and illustrated in Section 4 and the outcomes from sensitivity analysis are presented in Section 5. Conclusions are documented in Section 6.

## 2 CALCULATION METHODLOGIES

There are at least 3 relevant GHG emissions calculation methodologies which can be used for investigating comparative GHG benefits from the use of vegetable oils. Already mentioned is the methodology set out in the EC RED (EC, 2009) which has been developed specifically for biofuels. There is also the Renewable Fuels Agency (RFA) Technical Guidance (RFA, 2009) which currently supports the implementation of the Renewable Transport Fuels Obligation (RTFO) in the United Kingdom (UK). Of wider potential application is the British Standards Institution Publicly Accessible Standard (PAS) 2050 which has been designed for the "carbon footprinting" of any product or service. In addition to these methodologies, there is an approach which has been incorporated into the Biomass Environmental Assessment Tool ($BEAT_2$) which was developed for the Environment Agency (EA) and the Department of Environment, Food and Rural Affairs (DEFRA) for use with a range of biomass energy technologies including biofuels.

There are numerous differences in the details of these and other GHG emissions calculation methodologies and tools. The most prominent differences in the 3 methodologies considered for this study are summarised in Table 1. These concern whether the GHG emissions associated with the construction or manufacture, and maintenance of plant, equipment and machinery are included in calculations; the approach adopted for the allocating GHG emissions between the different products that can be generated by a production process; and how surplus electricity from combined heat and power (CHP) units are treated in the calculations.

The issue of plant, machinery and equipment is mainly relevant here in terms of agricultural activities, transportation and processing operations. Generally, the relative contribution of plant, equipment and machinery to total GHG emissions is small and can be ignored. However, this is not necessarily true for agricultural machinery

Table 1 Summary of Key Differences between Calculation Methodologies

| Methodology | Plant, Equipment and Machinery | Co-Product Allocation Procedures | Credits for Surplus Electricity (Exports) from CHP Units Used in Processing[(a)] |
|---|---|---|---|
| EC Renewable Energy Directive | Excluded | Energy content allocation | Credit based on total greenhouse gas emissions from generating electricity only using same fuel as CHP plant |
| RFA Technical Guidance | Excluded | Substitution credits wherever possible with price allocation otherwise | Credit based on total greenhouse gas emissions for marginal baseload electricity[(b)] (UK only) or average national grid electricity (all other countries) |
| PAS 2050 | Included if contribution to total greater than 1% | Price allocation | Credit based on total greenhouse gas emissions for average national grid electricity (all countries) |

Notes

(a) This specifies how any surplus electricity generated by the CHP plant used in processing (vegetable oil extraction and refining, and esterification and/or biolubricant production) is treated in calculations.

(b) Based on natural gas-fired combined cycle gas turbine plant (RFA, 2009)

where GHG emissions associated with manufacture are spread over a relatively short working life (in comparison with factory equipment, vehicles, etc.). Co-product allocation can be very important in GHG emissions calculations for biofuels, in general, and vegetable oils, biodiesel and biolubricant, in particular, since substantial amounts of by-products can arise during the production of the main product. Energy content allocation is based on the masses of the co-products and their calorific or heating values. Price allocation depends on the amounts of the co-products and their financial values. The use of substitution credits requires information on existing products which given by-products are likely to displace and the GHG emissions associated with the current production of these existing products. Consideration of the treatment of surplus electricity from CHP units is relevant here because such units are often used to provide heat and electricity for processing of vegetable oil and conversion to biodiesel and biolubricant.

Apart from possible methodological differences in treating surplus electricity from CHP units, there are also differences between the recommended values of GHG emissions factors for the electricity. All the methodologies assume that surplus electricity is exported from the CHP unit for use elsewhere, usually through the national electricity grid or network. Hence, methodologies adopt GHG emissions factors which either represent national average grid electricity or the supply of electricity from certain categories or types of power plant. Differences in subsequent GHG emissions factors for electricity are demonstrated in Table 2 which covers countries relevant to the workbooks used in this study. Differences in GHG emissions factors arise from a number of considerations. It will be noted that all factors, other than those quoted from North Energy sources (North Energy, 2009), are aggregated into equivalent $CO_2$.

Table 2 Comparison of Total GHG Emissions and Primary Energy Factors for Grid Electricity

| Country | Specification of Electricity | Source | Greenhouse Gas Emissions Factor | | | | Primary Energy Factor |
|---|---|---|---|---|---|---|---|
| | | | Carbon Dioxide ($g\ CO_2$/ MJ) | Methane ($g\ CH_4$/ MJ) | Nitrous Oxide ($g\ N_2O$/ MJ) | Total GHG Emissions (g eq. $CO_2$/ MJ) | (MJ/ MJ) |
| France | Average Grid | RFA, 2009 | n.s. | n.s. | n.s. | 22.8 | n.s. |
| | Average Grid | CT, 2008 | n.s. | n.s. | n.s. | 25.1 | n.s. |
| | Average Grid | North Energy, 2009 | 23.2 | 0.061 | 0.0014 | 25.0 | 3.067 |
| India | Average Grid | RFA, 2009 | n.s. | n.s. | n.s. | 253.0 | n.s. |
| | Average Grid | CT, 2008 | n.s. | n.s. | n.s. | 324.2 | n.s. |
| | Average Grid | North Energy, 2009 | 361.8 | 1.330 | 0.0289 | 400.9 | 4.564 |
| Malaysia | Average Grid | RFA, 2009 | n.s. | n.s. | n.s. | 137.0 | n.s. |
| | Average Grid | CT, 2008 | n.s. | n.s. | n.s. | 169.7 | n.s. |
| | Average Grid | North Energy, 2009 | 180.5 | 0.419 | 0.0070 | 192.2 | 2.282 |
| United Kingdom | Average Grid | RFA, 2009 | n.s. | n.s. | n.s. | 131.0 | n.s. |
| | Marginal Baseload | RFA, 2009 | n.s. | n.s. | n.s. | 106.0 | n.s. |
| | Average Grid | CT, 2008 | n.s. | n.s. | n.s. | 168.8 | n.s. |
| | Average Grid | North Energy, 2009 | 152.0 | 0.411 | 0.0030 | 162.4 | 2.952 |
| United States of America | Average Grid | RFA, 2009 | n.s. | n.s. | n.s. | 160.0 | n.s. |
| | Average Grid | CT, 2008 | n.s. | n.s. | n.s. | 195.8 | n.s. |
| | Average Grid | Wang, 1999 | 201.7 | 0.004 | 0.0028 | 202.7 | 2.543 |

This is achieved by applying relevant Global Warming Potentials (GWPs) to the contributions from $CH_4$ and $N_2O$ emissions. The values of GWPs used differ slightly between the different methodologies. Those adopted in the RFA Technical Guidance are obtained from the Intergovernmental Panel on Climate Change (IPCC) Third

Assessment Report (IPCC, 2001), whilst those recommended by the Carbon Trust in carbon footprinting with PAS 2050 are taken from the IPCC Fourth Assessment Report (IPCC, 2007). Changes in GWPs over time are summarised in Table 3. For consistency with the EC RED, the contributions from $CH_4$ and $N_2O$ emissions have been converted to the total GHG emissions factors using GWPs from the IPCC Third Assessment Report.

A more significant source of differences in GHG emissions factors for electricity is whether they only address direct emissions during electricity generation or also include emissions from the extraction and supply of fuels used in electricity generation. The North Energy GHG emissions factors include direct and indirect GHG emissions since they are based on input-output analysis of the UK energy sector (North Energy, 2006). There is evidence that the Carbon Trust uses a similar approach (CT, 2009) which is supported by similarities with North Energy GHG emissions factors for France and the UK. However, differences for GHG emissions factors between these sources are apparent for India and Malaysia. In general, the GHG emissions factors from the RFA Technical Guidance are significantly lower than those from all the other sources. This suggests that these GHG emissions factors may be based on only direct emissions, which would be implied by the apparent use of International Energy Agency (IEA) sectoral energy and emissions statistics (IEA, 2009). In all instances, it would seem that GHG emissions factors take into account grid losses.

In most instances, North Energy GHG emissions factors for electricity have been adopted for this study (North Energy, 2000 and 2009). This is because they are disaggregated into separate contributions from $CO_2$, $CH_4$ and $N_2O$ emissions necessary for workbook calculations. Additionally, these sources provide primary energy factors for electricity which have been derived consistently with the GHG emissions factors. The only exception has been the use of GHG emissions and primary energy factors for average grid electricity in the USA which have been adopted from the GREET model (Wang, 1999). The methodologies used within PAS 2050 and $BEAT_2$ assume that any surplus electricity from CHP units displaces average national grid electricity. This is also the case for the RFA Technical Guidance apart from GHG emissions calculations for UK-produced biofuels for which it is assumed that surplus electricity from CHP units displaces marginal electricity generated by natural gas-fired combined cycle gas turbine (CCGT) units. For consistency, it is assumed that the net thermal efficiency of such CCGT units is 54.3%, giving a total GHG emissions and primary energy factors for marginal electricity in the UK of 0.106 kg eq. $CO_2$/MJ and 1.934 MJ/MJ, respectively. In the case of the EC RED, surplus electricity from a CHP unit displaces electricity from a conventional power (only) unit using the same fuel as the CHP unit. Unfortunately, neither emissions factors nor net thermal efficiencies are quoted in the EC RED for such conventional power (only) units. Hence, for consistency, a net thermal efficiency for a natural gas-fired CCGT unit has been taken as 54.3%. The net thermal efficiencies for oil- and biomass-fired power (only) units have been assumed to be 25%.

Table 3 Global Warming Potentials for Methane and Nitrous Oxide (100 year time horizon)

| Source of Data | Global Warming Potential | |
|---|---|---|
| | Methane (kg eq. $CO_2$/kg $CH_4$) | Nitrous Oxide (kg eq. $CO_2$/kg $N_2O$) |
| Second Assessment Report (IPCC, 1996) | 21 | 310 |
| Third Assessment Report (IPCC, 2001) | 23 | 296 |
| Fourth Assessment Report (IPCC, 2007) | 25 | 298 |

# 3 WORKBOOKS

The MS Excel workbooks developed for this study are based on the same fundamental structure and layout of workbooks that have been prepared for a variety of applications and clients by North Energy (see, for example, BEAT, 2008). Each workbook consists of a collection of worksheets. Basically, the workbooks are structured around a Unit Flow Chart worksheet which describes the main features of the production pathway, or series of activities, involved in converting relevant biomass feedstock into final products which can be used as sources of heat and/or electricity, transport fuel or biolubricant. Individual worksheets are used to calculate GHG emissions and primary energy inputs associated with each stage in the production pathway. These calculations are then brought together in one of a number of Summary worksheets to determine total GHG emissions and primary energy inputs for each specified end product and application. Numerous modifications and extensions to previous versions of workbooks have been incorporated into the current workbooks to provide the necessary capabilities and functionalities needed to address the particular aspects of this study. These consist of the following important features:

- An Input worksheet which tabulates, in one place, all major input variables and assumptions for ease of use, especially in terms of sensitivity analysis. This worksheet contains a record of default values and assumptions as well as brief notes of explanation and sources of data.

- A series of Allocation worksheets, each one of which performs the basic calculations on co-product allocation consistent with relevant methodologies (energy content allocation for the EC RED, substitution credits for the RFA Technical Guidance, price allocation for PAS 2050 and $BEAT_2$, and mass allocation).

- A Fossil Reference worksheet which contains details of the calculation of total GHG emissions and primary energy inputs for displaced conventional sources of energy and lubricant (heat from fuel oil and natural gas; electricity from fuel oil, natural gas and the national grid; combined heat and power from fuel oil and natural gas; diesel fuel from conventional crude oil for transport; and motor oil from conventional crude oil disposed of by incineration).

- An overall Summary worksheet which brings together all the results from the individual Summary worksheets and provides direct comparison with displaced conventional sources of energy and lubricant so that unit and net GHG and primary energy savings can be determined.

The workbooks are fully transparent and the sources of all assumptions and data are referenced. “Drop down” menus are included for a number of variables and assumptions to assist with the routine generation of results, especially for sensitivity analysis. The filenames of the specific version of the workbooks used to produce the results presented here are documented in Table 4. This includes a summary of the main features represented by the quoted default values and assumptions which are referred to here as the “Base Case”. In particular, it will be seen that these Base Cases reflect the production and conversion of end products (refined vegetable oil, biodiesel or biolubricant) from used cooking oil and oilseed rape in the UK; and the production of refined vegetable oil from soy beans in the USA, from sunflowers in France, oil palm in

Table 4 Summary of Workbook Details and Main Features of Base Cases

| Biomass Feedstock | MS Excel Filename | Summary of Main Features of Base Case |
|---|---|---|
| Used Cooking Oil | DECCbd_rvo_09_v18 | Used cooking oil recovered, cleaned (for refined oil) and processed (for biodiesel or biolubricant) in the UK. Natural gas-fired boiler and grid electricity used for cleaning and processing. |
| Oilseed Rape | DECCbd_osr_09_v32 | Oilseed rape cultivated, harvested and dried, with oil extraction and refining (for refined oil) and processing (for biodiesel or biolubricant), in the UK. Natural gas-fired CHP used for extraction, refining and processing[(a)]. |
| Soy Bean | DECCbd_soy_09_v21 | Soy beans cultivated, harvested and dried, with oil extraction and refining (for refined oil), in the USA. Natural gas-fired CHP used for extraction and refining. Refined oil shipped to UK. Processing (for biodiesel or biolubricant) with natural gas-fired boiler and grid electricity in the UK[(b)]. |
| Sunflowers | DECCbd_sf_09_v14 | Sunflowers cultivated and harvested, with oil extraction and refining (for refined oil), in France. Natural gas-fired CHP used for extraction and refining. Refined oil shipped to UK. Processing (for biodiesel or biolubricant) with natural gas-fired boiler and grid electricity in the UK[(b)]. |
| Oil Palm | DECCbd_palm_09_v26 | Oil palms cultivated and harvested, with oil extraction and refining (for refined oil), in Malaysia. Biomass-fired[(c)] CHP used for extraction and refining. Refined oil shipped to UK. Processing (for biodiesel or biolubricant) with natural gas-fired boiler and grid electricity in the UK[(b)]. |
| Jatropha | DECCbd_jat_09_v14 | Jatropha cultivated and harvested on a commercial scale, with oil extraction and refining (for refined oil), in India. Biomass-fired[(d)] CHP used for extraction and refining. Refined oil shipped to UK. Processing (for biodiesel or biolubricant) with natural gas-fired boiler and grid electricity in the UK[(b)]. |

Notes

(a) Assuming an integrated oil extraction, refining and esterification plant, where appropriate.

(b) Assuming a separate esterification plant, where appropriate.

(c) Assuming empty fruit bunches, kernel fibre and shells providing biomass for energy production.

(d) Assuming jatropha prunings providing biomass for energy production.

Malaysia, and jatropha in India, with subsequent conversion (to biodiesel or biolubricant) in the UK[2]. In all instances, it is assumed that the use of end products and displacement of conventional sources of energy and lubricants occurs in the UK. The Base Case reflects GHG emissions calculations assuming the EC RED methodology.

Additional features had to be incorporated for the evaluation of biolubricant and its comparison with lubricant (motor oil) derived from conventional crude oil. This was because complete evaluation requires consideration of the use and eventual fate of the biolubricant and the lubricant which it could displace. When refined vegetable oil and biodiesel are used as sources of energy, there is effectively no waste for requires disposal. However, this is not the case for biolubricants and conventional lubricants. The fate of the biogenic and fossil carbon in these materials has a strong influence on their full life cycle GHG emissions (Mortimer et al, 2009). In particular, various methods of disposal are available. However, given expected future restrictions on landfill disposal, it was assumed that the main options would be incineration with or without energy recovery (in the form of electricity). The advantages or disadvantages of this in terms of GHG emissions depends on the balance between the direct emissions of combustion during incineration and the avoided emission of displaced electricity (taken to be UK average grid electricity). This balance is further complicated by the nature of the carbon content of the biolubricant and how it affects the calculation of relevant direct emissions during incineration. It should be noted that it has been assumed that a given fraction of the biolubricant is derived from fossil rather than biogenic sources. Hence, when burnt, the $CO_2$ from the fossil carbon will add to the $CO_2$ in the atmosphere and has to be included accordingly. In contrast the $CO_2$ from biogenic sources will be offset by $CO_2$ absorbed from the atmosphere during original biomass feedstock growth. In the case of conventional lubricant, all the $CO_2$ is derived from fossil carbon and is accounted as an addition to the atmosphere.

A further complication in the evaluation of biolubricant arises from losses during use and the subsequent fate of contained carbon. Unfortunately, during the course of this study, no firm evidence could be found on the actual fate of carbon in lost biolubricant (and conventional lubricant). Consequently, options were established to address most possibilities which consisted of complete sequestration (carbon "locked" away with no eventual GHG emissions); conversion to $CO_2$ (with impacts on the atmosphere only for $CO_2$ derived from fossil carbon); or conversion to $CH_4$ (with impacts on the atmosphere regardless of whether this is derived from fossil or biogenic carbon). To provide suitable functionality, the possibility of varying biolubricant (and conventional lubricant) losses, and changing proportions of carbon sequestration, conversion to $CO_2$, and conversion to $CH_4$ were incorporated into the workbooks.

In the absence of specific evidence and to avoid yet more complications, it was assumed that there were no differences in the performance and fate of biolubricant compared with conventional lubricant. In terms of the so-called "use phase", this meant that an equal amount of conventional lubricant was replaced by biolubricant. It would, however, be possible to modify this assumption and that concerning the details of the relevant fates of biolubricant and conventional lubricant if specific data on this were to become available in the future.

[2] It has been necessary to assume that all imported vegetable oil is converted to biodiesel in a separate esterification plant using a natural gas-fired boiler and imported electricity because the CHP specifications of an integrated plant cannot be uniquely defined without information on the requirements of all processed oils.

# 4 RESULTS

## 4.1 Greenhouse Gas Emissions

Total GHG emissions calculated using the workbooks consisted of contributions from $CO_2$ emissions, and $CH_4$ and $N_2O$ emissions converted with relevant GWPs to equivalent (eq.) $CO_2$. Basic results are expressed in kilograms (kg) eq. $CO_2$ per megajoule ($10^6$ joules or MJ) for energy end-use applications (heat and/or electricity, and transport fuels) and kg eq. $CO_2$ per tonne (t) for refined vegetable oil, biodiesel and biolubricant. These basic results are used to evaluate net savings, which are the proportional difference in total GHG emissions of the vegetable oil end-use and the conventional options it displaces. The basic results from the workbooks represent the Base Case default values and assumptions which are in compliance with the EC RED methodology.

### 4.1.1 Total Greenhouse Gas Emissions

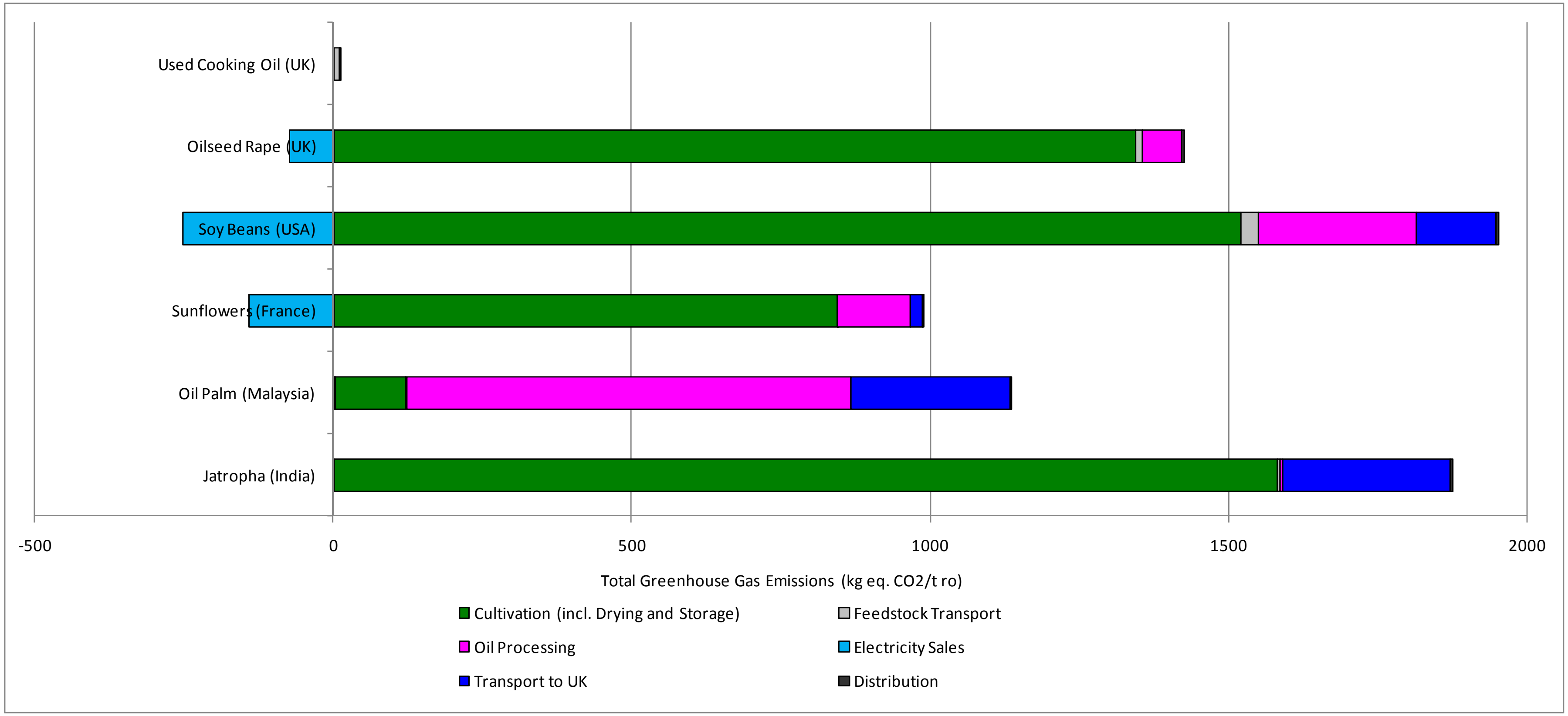
Basic results from the workbooks for refined vegetable oil are presented in Table 5. These are expressed in terms of kg eq. $CO_2$ per t of refined vegetable oil (ro) and, by adjustment with the relevant net calorific values (lower heating values; LHVs), kg eq. $CO_2$ per MJ. Significant differences in total GHG emissions will be noted from Table 5 as well as some less marked differences in net calorific values which were obtained from published sources.

Table 5 Total GHG Emissions Associated with the Production of Refined Vegetable Oil

| Refined Vegetable Oil: Base Cases | Used Cooking Oil | Oilseed Rape | Soy Bean | Sun-flowers | Oil Palm | Jatropha |
|---|---|---|---|---|---|---|
| Total GHG Emissions (kg eq. $CO_2$/t ro) | 13 ± 1 | 1,351 ± 1 | 1,698 ± 162 | 848 ± 4 | 1,136 ± 1 | 1,872 ± 63 |
| Net Calorific Value (MJ/t ro) | 37,030 | 35,000 | 39,500 | 39,400 | 36,770 | 39,500 |
| Total GHG Emissions (kg eq. $CO_2$/MJ) | 0.0004 | 0.0386 | 0.0430 ± 0.0041 | 0.0215 ± 0.0001 | 0.0309 | 0.0474 ± 0.0016 |

There are a number of causes of differences in total GHG emissions for these refined vegetable oils. These can be examined in detail in the workbooks. However, an overview can be gained by considering the breakdown of contributions to total GHG emissions by stage of production shown in Figure 1. In general, the total GHG emissions for refined vegetable oil derived from used cooking oil are very low because it is collected as a waste product (with no GHG emissions associated with its previous use) and the only processing involved is simple cleaning. In contrast, all the other vegetable oils considered here have to be derived from cultivated biomass feedstocks with possibly significant GHG emissions associated with nitrogen (N) fertiliser manufacture, soil $N_2O$ emissions and diesel fuel consumption. The extent of GHG emissions from N fertiliser manufacture and soil $N_2O$ emissions varies with the N fertiliser application rate (relatively low for oil palm and relatively high for oilseed rape). Total GHG emissions associated with oil extraction and refining depend partly on the sources of

Figure 1 Breakdown of Contributions to Total GHG Emissions for Refined Vegetable Oil Production



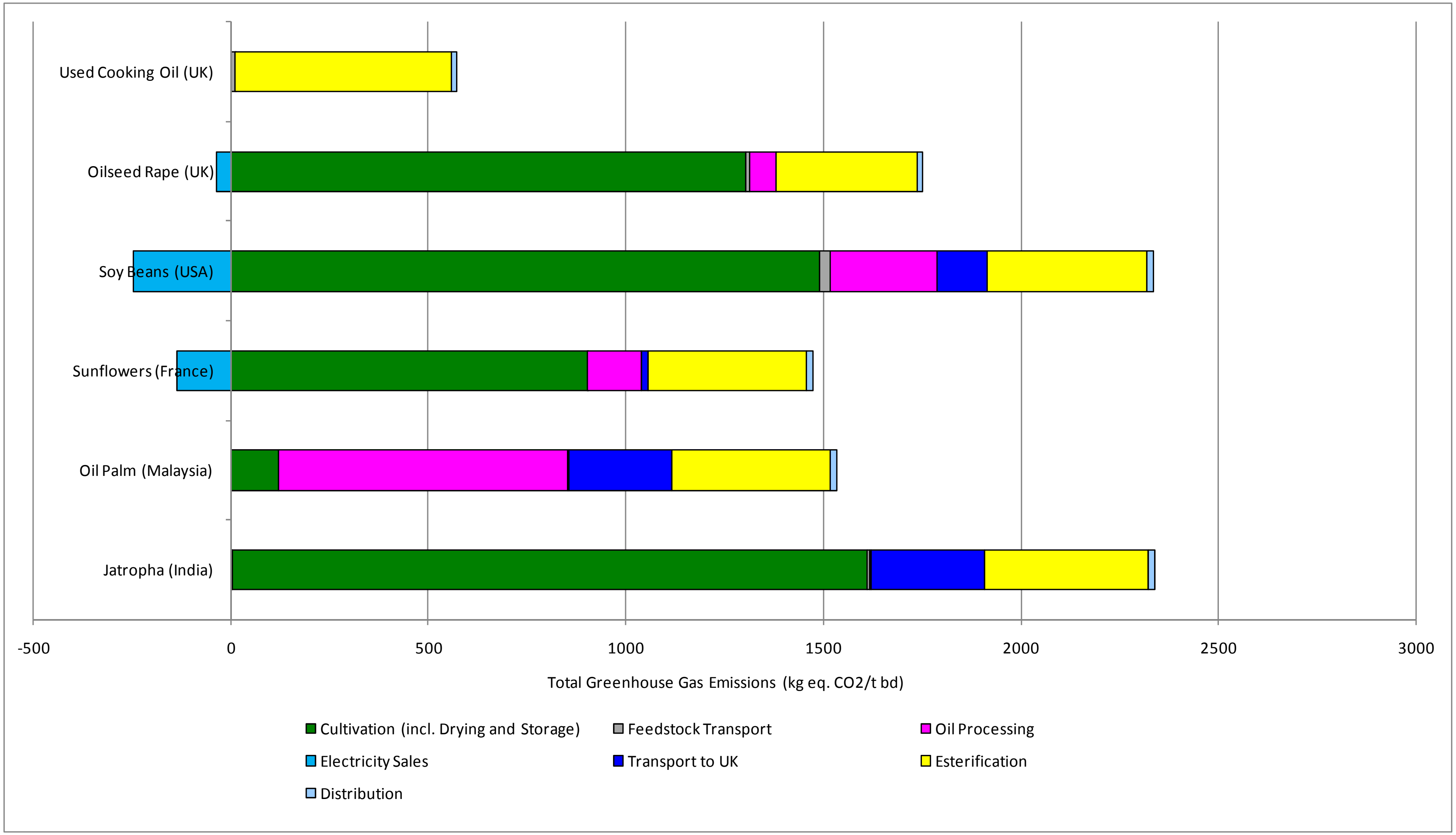
heat and electricity used by these processes (oilseed rape, soy bean and sunflower processing is assumed to used natural gas-fired CHP units and oil palm and jatropha processing are assumed to use biomass-fired CHP units in the Base Cases). In the case of vegetable oils extracted and refined using natural gas-fired CHP units, noticeable GHG emissions credits occur due to surplus electricity sales which, under the EC RED methodology, displace natural gas–fired power only generation. Processing GHG emissions are also partly dependent on specific aspects of such processing (such as substantial $CH_4$ emissions from palm oil effluent ponds in the Base Case for oil palm). GHG emissions from transportation of refined vegetable oils by ship to the UK are also added for certain biomass feedstocks (soy bean, sunflowers, oil palm and jatropha) and these vary with the assumed source locations and subsequent distances (relatively low for sunflowers in France and relatively high for oil palms in Malaysia and jatropha in India).

Basic results for biodiesel derived from these biomass feedstocks are shown in Table 6. These are expressed in terms of kg eq. $CO_2$ per t of biodiesel (bd) and, by adjustment with the net calorific value of 37,270 MJ per t (RFA, 2009), kg eq. $CO_2$ per MJ. Differences between results are a little less pronounced due to the fact that all these results include relatively significant GHG emissions contributions from esterification. In the Base Case for biodiesel production from oilseed rape in the UK, it is assumed that heat and electricity for oil extraction and refining, and esterification is provided by a natural gas-fired CHP unit. For the Base Case with biodiesel production from used cooking oil, it is assumed that a natural gas-fired boiler and imported electricity is used in oil cleaning and refining, and esterification since plant size may not support the use of a dedicated CHP unit. For the Base Cases with biodiesel production from soy bean, sunflowers, oil palm and jatropha, it has been necessary to assume that esterification in the UK is undertaken with heat from a natural gas-fired boiler and imported electricity. In practice, it is likely that a natural gas-fired CHP unit would be used for the esterification of a mixture of imported and home-produced vegetable oils. However, it was not possible to incorporate this assumption into the workbooks since the partial use of a CHP unit cannot be accommodated. In particular, the share of the GHG emissions credit from the sale of surplus electricity from the CHP unit cannot be determined. The addition of these GHG emissions associated with esterification is illustrated in Figure 2.

Table 6 Total GHG Emissions Associated with the Production of Biodiesel

| Biodiesel: Base Cases | Used Cooking Oil | Oilseed Rape | Soy Bean | Sun-flowers | Oil Palm | Jatropha |
|---|---|---|---|---|---|---|
| Total GHG Emissions (kg eq. $CO_2$/t bd) | 568 ±78 | 1,609 ± 41 | 2,461 ± 164 | 1,391 ± 42 | 1,744 ± 42 | 2,729 ± 78 |
| Total GHG Emissions (kg eq. $CO_2$/MJ) | 0.0153 ± 0.0021 | 0.0459 ± 0.0011 | 0.0560 ± 0.0044 | 0.0358 ± 0.0011 | 0.0411 ± 0.0011 | 0.0626 ± 0.0021 |

Figure 2 Breakdown of Contributions to Total GHG Emissions for Biodiesel Production



The basic results, in terms of grams (g) eq. $CO_2$ per MJ, derived here for biodiesel can be compared with the typical values quoted in the EC RED (EC, 2009). This comparison is provided in Table 7 which shows some strong similarities between results, especially for biodiesel produced from oilseed rape, soy bean and sunflowers. The result derived for biodiesel from used cooking oil is slightly higher from the workbook than the EC RED, whilst that generated for biodiesel from oil palm is somewhat lower. The possible causes of these differences cannot be determined here due to the lack of published details on the typical values given in the EC RED. Comparison of results for biodiesel from jatropha was not possible as this production pathway is not covered in the EC RED.

Table 7 Comparison of Total GHG Emissions Associated with Biodiesel Production between Workbooks and the EC RED

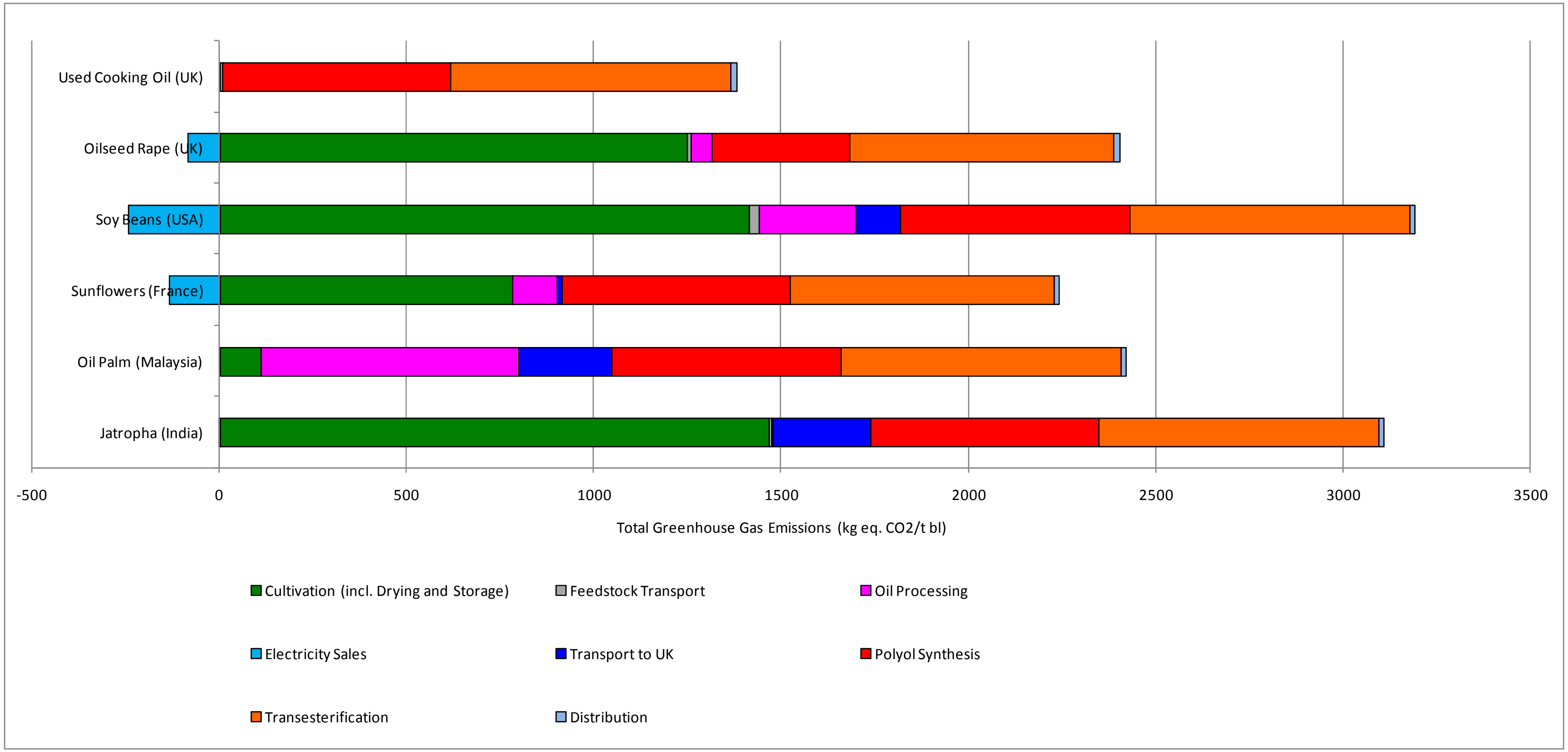
| Biodiesel (g eq. $CO_2$/MJ) | Used Cooking Oil | Oilseed Rape | Soy Bean | Sun-flowers | Oil Palm | Jatropha |
|---|---|---|---|---|---|---|
| This Study: Base Cases | 15 ± 2 | 46 ± 1 | 56 ± 4 | 36 ± 1 | 41 ± 1 | 63 ± 2 |
| RED Typical Values (EC, 2009) | 10 | 46 | 50 | 35 | 54 | not available |

Basic results for biolubricant derived from these biomass feedstocks are given in Table 8. These are expressed in terms of kg eq. $CO_2$ per t of biolubricant (bd). As with the results for biodiesel, these reflect the initial production of vegetable oil with a fixed contribution of GHG emissions associated with polyol synthesis and transesterification. In all Base Cases, it is assumed that these final stages of biolubricant production occur in the UK with heat provided by a natural gas-fired boiler and electricity imported from the national grid. For comparison, the total GHG emissions associated with the production of motor oil from conventional crude oil has been taken as 335 kg eq, $CO_2$ per t. This was determined using published data on the GHG emissions factor for the production of non-fuel petroleum products (BRE, 2000) and a net calorific value for biolubricant of 40,900 MJ per t (DECC, 2009). The breakdown of contributions to total GHG emissions associated with biolubricant production is illustrated in Figure 3. It should be noted that the results in Table 8 and Figure 3 only include production and exclude the use and disposal phases for biolubricant.

Table 8 Total GHG Emissions Associated with Biolubricant Production

| Biolubricant: Base Cases | Used Cooking Oil | Oilseed Rape | Soy Bean | Sun-flowers | Oil Palm | Jatropha |
|---|---|---|---|---|---|---|
| Total GHG Emissions (kg eq. $CO_2$/t bl) | 1,379 ± 67 | 2,318 ± 67 | 2,948 ± 165 | 2,109 ± 67 | 2,421 ± 67 | 3,107 ± 89 |

Figure 3 Breakdown of Contributions to Total GHG Emissions for Biolubricant Production



#### 4.1.2 Net Greenhouse Gas Emissions Savings

Comparisons between the GHG emissions associated with the production and use of vegetable oils and their derivative products and displaced current (fossil fuel-derived) alternatives can be undertaken in many different ways. The most common and most simply-expressed means is through net GHG emissions savings[3]. Such net savings relate to the difference between the total GHG emissions of the end product and its displaced current alternative. These net savings can be presented in at least two different forms; unit net savings and percentage net savings. Unit net GHG emissions savings are just the difference in total GHG emissions per unit of specified product, such as kg eq. $CO_2$ per t of refined vegetable oil, and those of its displaced alternative:

$$S_u = (G_f - G_v)$$

$S_u$ = Unit net GHG emissions savings of vegetable oil-derived product or end-use (kg eq. $CO_2$/unit)
$G_f$ = Total GHG emissions of fossil fuel-derived product or end-use (kg eq. $CO_2$/unit)
$G_v$ = Total GHG emissions of vegetable oil-derived product or end-use (kg eq. $CO_2$/unit)

Alternatively, unit net savings can be determined, or normalised, in terms of other end products (biodiesel or biolubricant) or end-uses (MJ of heat and/or electricity).

Percentage net GHG emissions savings are the difference in total GHG emissions between the vegetable oil option and its displaced alternative relative to the total GHG emissions associated with this displaced alternative, written as percentage (%):

$$S_p = \frac{(G_f - G_v)}{G_f} \times 100\%$$

$S_p$ = Percentage net GHG emissions savings of the vegetable oil-derived product or end-use (%)
$G_f$ = Total GHG emissions of fossil fuel-derived product or end-use (kg eq. $CO_2$/unit)
$G_v$ = Total GHG emissions of vegetable oil-derived product or end-use (kg eq. $CO_2$/unit)

These two measures of net GHG emissions savings have different interpretations when considering possibilities for maximising GHG emissions benefits. In the case of unit net GHG emissions savings, these can be used to investigate maximisation of the *absolute change* in total GHG emissions (as indicated by kg eq. $CO_2$). This measure is, therefore, relevant for determining the maximum amount of total GHG emissions that can be saved. Alternatively, percentage net GHG emissions savings are relevant to maximisation of the *relative change* in total GHG emissions relative to their current level (as expressed as a %). This means that percentage net GHG emissions savings are relevant for determining the maximum change in total GHG emissions that can be achieved.

[3] It should be noted that in all following presentations and discussions of results in the forms of net savings (GHG emissions or primary energy), a positive value equates to a decrease (saving or reduction in GHG emissions or primary energy use) and a negative value equates to an increase (in GHG emissions or primary energy use).

For convenience, the results for unit net GHG emissions savings in Table 9 have been normalised to 1 kg of refined vegetable oil. This means that these results indicate the amount of total GHG emissions saved by using refined vegetable oil, from different biomass feedstocks, in different ways. Given the scope and functionality incorporated into the workbooks, a large number of results can be generated, as demonstrated by Tables 9 and 10. This range of results reflects the various combinations of using vegetable oils and their displacement potential. However, such a large number of results can be confusing either when they are being interpreted, in general, and when, they are being used to identify options which maximise total GHG emissions savings, in particular. Consequently, a simple colour coding system has been introduced to indicate the top 4 ranked absolute savings of total GHG emissions (in Table 9) and relative changes in total GHG emissions (in Table 10).

From Table 9, it can be seen that the highest absolute savings in total GHG emissions can be achieved by using refined vegetable oil derived from used cooking oil in a CHP unit to displace heat generated from fuel oil and electricity from the grid. Using refined vegetable oil in this way also maximises absolute savings in total GHG emissions associated with soy beans, sunflowers, oil palms and jatropha. The only exception is oilseed rape for which maximum absolute savings in total GHG emissions occur when biodiesel derived from this feedstock is used in a heat (only) boiler to displace fuel oil. In terms of the next highest (second ranked) absolute savings in total GHG emissions, positions are reversed for these biomass feedstocks. Hence, in all instances, the top two rankings in absolute savings are occupied by refined vegetable oil used in a CHP unit to displace a fuel oil-fired heat (only) boiler with electricity from the grid, and biodiesel used in a heat (only) boiler to displace fuel oil for heating. It should be noted that this latter application of biodiesel achieves higher total GHG emissions savings than its use as a transport fuel to displace diesel derived from conventional crude oil (+11% for biodiesel from used cooking oil and UK oilseed rape; +55% for biodiesel from US soy beans; +15% for biodiesel from French sunflowers; +21% for biodiesel from Malaysian oil palms; and +36% for biodiesel from Indian jatropha)

In general terms, it should be noted that most pathways and end-use applications produce total GHG savings relative to fossil fuel-derived alternatives. The main exceptions to this pattern (negative savings) are refined vegetable oils (from oilseed rape, soy beans, oil palms and jatropha) used for electricity (only) generation displacing natural gas-fired electricity (only) generation; refined vegetable oils (from soy bean and jatropha) used in a CHP unit to displace natural gas-fired CHP; biodiesel (from oilseed rape, soy beans, sunflowers, oil palms and jatropha) used in electricity (only) generation to displace natural gas-fired electricity (only) generation; biodiesel (from soy beans and jatropha) used in electricity (only) generation to displace fuel oil-fired electricity (only); biodiesel (from oilseed rape, soy beans and jatropha) used in electricity (only) generation to displace grid electricity; and biolubricant (from oilseed rape, soy beans, sunflowers, oil palms and jatropha) to displace fossil fuel-derived motor oil. A similar pattern of relative changes in total GHG emissions is apparent in Table 10. In general, end products and end-uses from used cooking oil produce the highest overall percentage net GHG emissions savings. The clearest trend is that top rankings in relative changes in total GHG emissions for all pathways consist of refined vegetable oil used in a CHP unit to displace fuel oil-fired heat (only) and grid electricity.

Table 9 Comparison of Unit Net GHG Emissions Savings per Unit of Refined Vegetable Oil for Base Cases

| Product | End-Use | Displacing | Net Greenhouse Gas Emissions Savings per Unit of Vegetable Oil (kg eq. $CO_2$/kg ro) | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Used Cooking Oil | Oilseed Rape | Soy Bean | Sun-flowers | Oil Palm | Jatropha |
| Refined Oil | Electricity (Only) | Natural Gas-fired Electricity | 1.023 | -0.348 | -0.569 | 0.283 | -0.083 | -0.762 |
| Refined Oil | Electricity (Only) | Fuel Oil-fired Electricity | 1.827 | 0.430 | 0.309 | 1.159 | 0.735 | 0.116 |
| Refined Oil | Electricity (Only) | Grid Electricity | 1.455 | 0.069 | -0.097 | 0.753 | 0.356 | -0.290 |
| Refined Oil | CHP Heat and Electricity | Natural Gas-fired CHP | 1.815 | 0.418 | 0.301 | 1.151 | 0.724 | 0.124 |
| Refined Oil | CHP Heat and Electricity | Fuel Oil-fired CHP | 2.324 | 0.911 | 0.857 | 1.706 | 1.242 | 0.681 |
| Refined Oil | CHP Heat and Electricity | Natural Gas-fired Heat and Grid Electricity | 2.594 | 1.172 | 1.152 | 2.000 | 1.516 | 0.975 |
| Refined Oil | CHP Heat and Electricity | Fuel Oil-fired Heat and Grid Electricity | 3.239 | 1.798 | 1.857 | 2.703 | 2.173 | 1.681 |
| Refined Oil | Biolubricant | Motor Oil | 0.164 | -0.805 | -1.457 | -0.632 | -0.920 | -1.622 |
| Biodiesel | Heat (Only) | Natural Gas-fired Heat (Only) | 2.047 | 0.921 | 0.532 | 1.143 | 1.148 | 0.328 |
| Biodiesel | Heat (Only) | Fuel Oil-fired Heat (Only) | 3.037 | 1.891 | 1.508 | 2.039 | 2.118 | 1.298 |
| Biodiesel | CHP Heat and Electricity | Natural Gas-fired CHP | 1.285 | 0.067 | 0.091 | 0.494 | 0.300 | -0.415 |
| Biodiesel | CHP Heat and Electricity | Fuel Oil-fired CHP | 1.795 | 0.566 | 0.596 | 0.955 | 0.899 | 0.084 |
| Biodiesel | CHP Heat and Electricity | Natural Gas-fired Heat and Grid Electricity | 2.064 | 0.830 | 0.863 | 1.198 | 1.163 | 0.348 |
| Biodiesel | CHP Heat and Electricity | Fuel Oil-fired Heat and Grid Electricity | 2.710 | 1.463 | 1.504 | 1.782 | 1.795 | 0.980 |
| Biodiesel | Electricity (Only) | Natural Gas-fired Electricity | 0.494 | -0.599 | -0.972 | -0.257 | -0.373 | -1.105 |
| Biodiesel | Electricity (Only) | Fuel Oil-fired Electricity | 1.297 | 0.189 | -0.176 | 0.470 | 0.414 | -0.318 |
| Biodiesel | Electricity (Only) | Grid Electricity | 0.925 | -0.176 | -0.545 | 0.133 | 0.050 | -0.682 |
| Biodiesel | Transport Fuel | Diesel | 2.447 | 1.313 | 0.969 | 1.545 | 1.483 | 0.723 |

Colour Codes for Ranking of Highest Net Greenhouse Gas Emissions Savings per Kilogram of Vegetable Oil within Each Pathway for Oil Production

| | |
|---|---|
| First | |
| Second | |
| Third | |
| Fourth | |

Table 10 Comparison of Percentage Net GHG Emissions Savings Base Cases

| Product | End-Use | Displacing | Net Greenhouse Gas Emissions Savings (%) | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Used Cooking Oil | Oilseed Rape | Soy Bean | Sun-flowers | Oil Palm | Jatropha |
| Refined Oil | Electricity (Only) | Natural Gas-fired Electricity | 99 | -35 | -50 | 25 | -8 | -67 |
| Refined Oil | Electricity (Only) | Fuel Oil-fired Electricity | 99 | 24 | 15 | 58 | 39 | 6 |
| Refined Oil | Electricity (Only) | Grid Electricity | 99 | 5 | -6 | 47 | 24 | -18 |
| Refined Oil | CHP Heat and Electricity | Natural Gas-fired CHP | 99 | 24 | 15 | 58 | 39 | 6 |
| Refined Oil | CHP Heat and Electricity | Fuel Oil-fired CHP | 99 | 40 | 34 | 67 | 52 | 27 |
| Refined Oil | CHP Heat and Electricity | Natural Gas-fired Heat and Grid Electricity | 99 | 46 | 40 | 70 | 57 | 34 |
| Refined Oil | CHP Heat and Electricity | Fuel Oil-fired Heat and Grid Electricity | 100 | 57 | 52 | 76 | 66 | 47 |
| Refined Oil | Biolubricant | Motor Oil | 18 | -86 | -156 | -68 | -98 | -173 |
| Biodiesel | Heat (Only) | Natural Gas-fired Heat (Only) | 77 | 35 | 20 | 48 | 44 | 13 |
| Biodiesel | Heat (Only) | Fuel Oil-fired Heat (Only) | 83 | 53 | 42 | 62 | 59 | 36 |
| Biodiesel | CHP Heat and Electricity | Natural Gas-fired CHP | 70 | 4 | -5 | 30 | 22 | -23 |
| Biodiesel | CHP Heat and Electricity | Fuel Oil-fired CHP | 77 | 25 | 26 | 45 | 39 | 4 |
| Biodiesel | CHP Heat and Electricity | Natural Gas-fired Heat and Grid Electricity | 79 | 32 | 33 | 51 | 46 | 14 |
| Biodiesel | CHP Heat and Electricity | Fuel Oil-fired Heat and Grid Electricity | 83 | 46 | 47 | 61 | 56 | 31 |
| Biodiesel | Electricity (Only) | Natural Gas-fired Electricity | 48 | -59 | -95 | -27 | -37 | -109 |
| Biodiesel | Electricity (Only) | Fuel Oil-fired Electricity | 71 | 10 | -10 | 28 | 23 | -18 |
| Biodiesel | Electricity (Only) | Grid Electricity | 63 | -12 | -37 | 10 | 3 | -47 |
| Biodiesel | Transport Fuel | Diesel | 82 | 45 | 33 | 57 | 50 | 25 |

Colour Codes for Ranking of Highest Net Greenhouse Gas Emissions Savings within Each Pathway for Oil Production

| | |
|---|---|
| First | |
| Second | |
| Third | |
| Fourth | |

## 4.2 Primary Energy Inputs

Primary energy is a measure of energy resource depletion. In this study, primary energy is taken to be equal to the total amount of energy consumed from depletable energy resources which consist of fossil and nuclear fuels. Biomass and other forms of renewable energy are excluded from this definition of primary energy.

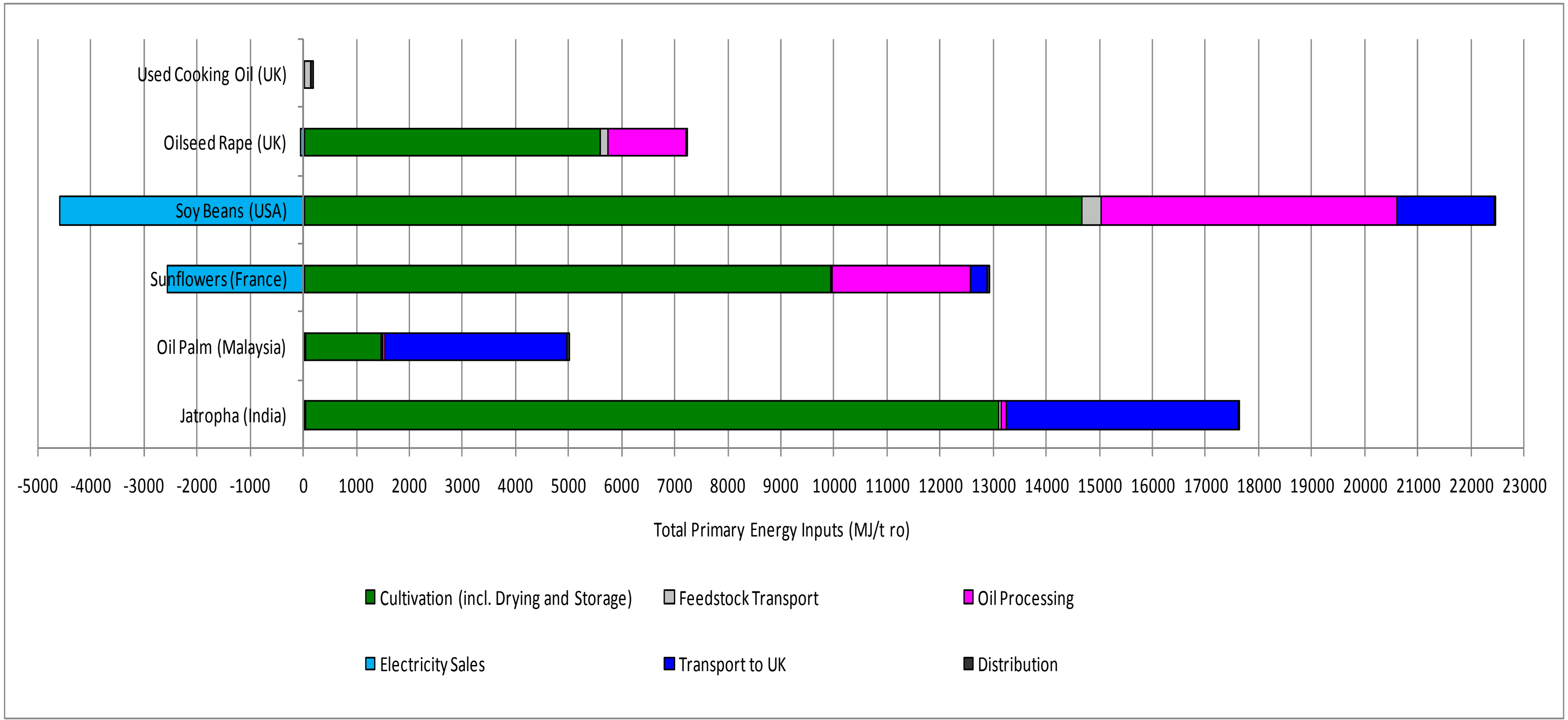
### 4.2.1 Total Primary Energy Inputs

Basic results from the workbooks for refined vegetable oil are presented in Table 11. These are expressed in terms of MJ per t of refined vegetable oil (ro) and, by adjustment with the relevant net calorific values, MJ per MJ. Significant differences in total GHG emissions will be noted from Table 11. However, the causes of these differences in primary energy inputs are not the same as those for associated total GHG emissions. This can be explained by referring to the breakdown of contributions to total primary energy inputs for refined vegetable oils illustrated in Figure 4. In particular, the pattern of contributions is different for biomass feedstock cultivation in Figures 1 and 4. The main reason for this is that some specific contributions (N fertiliser manufacture and soil $N_2O$ emissions) which are significant in terms of total GHG emissions are less important (for N fertiliser manufacture) or non-existent (for soil $N_2O$ emissions) for primary energy inputs. In general, the magnitude of total GHG emissions is not always reflected in primary energy intensity.

Table 11 Total Primary Energy Inputs Associated with Production of Refined Vegetable Oil

| Refined Vegetable Oil: Base Cases | Used Cooking Oil | Oilseed Rape | Soy Bean | Sun-flowers | Oil Palm | Jatropha |
|---|---|---|---|---|---|---|
| Total Primary Energy Inputs (MJ/t ro) | 173 ± 10 | 7,160 ± 27 | 17,870 ± 2,065 | 10,339 ± 301 | 4,995 ± 28 | 17,635 ± 712 |
| Net Calorific Value (MJ/t ro) | 37,030 | 35,000 | 39,500 | 39,400 | 36,770 | 39,500 |
| Total Primary Energy Inputs (MJ/MJ) | 0.005 | 0.205 ± 0.001 | 0.452 ± 0.052 | 0.262 ± 0.008 | 0.136 ± 0.001 | 0.446 ± 0.019 |

Figure 4 Breakdown of Contributions to Total Primary Energy Inputs for Refined Vegetable Oil Production



Basic results for biodiesel derived from these biomass feedstocks are shown in Table 12. These are expressed in terms of MJ per t of biodiesel (bd) and, by adjustment with the net calorific value of 37,270 MJ per t (RFA, 2009), MJ per MJ. As with the results for total GHG emissions in Table 6, a fixed primary energy input is added for esterification. As before, in the Base Case, esterification was assumed to be undertaken with heat from a natural gas-fired boiler and grid electricity except for the conversion of vegetable oil from oilseed rape where a natural gas-fired CHP unit was used. The resulting addition of primary energy is further demonstrated in Figure 5 which shows the breakdown of contributions to total primary energy inputs for biodiesel produced from different biomass feedstocks.

Table 12 Total Primary Energy Inputs Associated with Production of Biodiesel

| Biodiesel: Base Cases | Used Cooking Oil | Oilseed Rape | Soy Bean | Sun-flowers | Oil Palm | Jatropha |
|---|---|---|---|---|---|---|
| Total Primary Energy Inputs (MJ/t bd) | 7,917 ±1099 | 11,150 ± 574 | 25,240 ± 216 | 18,214 ± 675 | 10,704 ±585 | 24,755 ±988 |
| Total Primary Energy Inputs (MJ/MJ) | 0.214 ±0.029 | 0.319 ± 0.015 | 0.635 ± 0.057 | 0.469 ± 0.018 | 0.298 ± 0.016 | 0.634 ± 0.027 |

Basic results for biolubricant derived from these biomass feedstocks are given in Table 13. These are expressed in terms of MJ per t of biolubricant (bd). As with the results for biodiesel, these reflect the initial production of vegetable oil with a fixed contribution of primary energy inputs for polyol synthesis and transesterification. In all Base Cases, it is assumed that these final stages of biolubricant production occur in the UK with heat provided by a natural gas-fired boiler and electricity imported from the national grid. For comparison, the total primary energy inputs for the production of motor oil from conventional crude oil have been taken as 45,399 MJ per t. This was determined using published data on the GHG emissions factor of 1.11 MJ per MJ for the production of non-fuel petroleum products (BRE, 2000) and a net calorific value for biolubricant of 40,900 MJ per t (DECC, 2009). The breakdown of contributions to the total primary energy inputs of biolubricant production from different biomass feedstocks is illustrated in Figure 6.

Table 13 Total Primary Energy Inputs Associated with Production of Biolubricant

| Biolubricant: Base Cases | Used Cooking Oil | Oilseed Rape | Soy Bean | Sun-flowers | Oil Palm | Jatropha |
|---|---|---|---|---|---|---|
| Total Primary Energy Inputs (MJ/t bl) | 22,918 ± 931 | 24,911 ± 931 | 39,265 ± 2136 | 31,755 ± 976 | 27,372 ± 932 | 38,491 ± 1174 |

Figure 5 Breakdown of Contributions to Total Primary Energy Inputs for Biodiesel Production

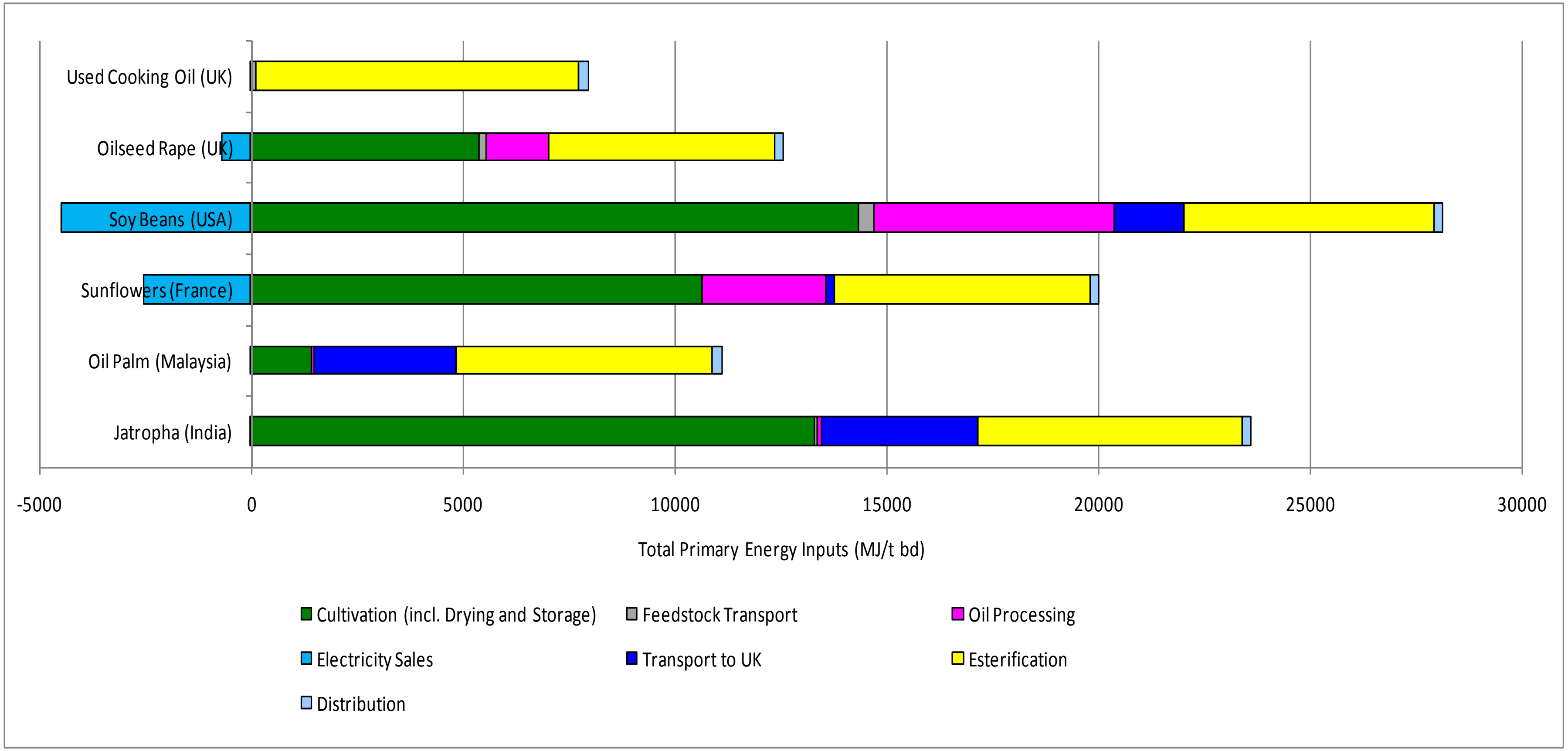
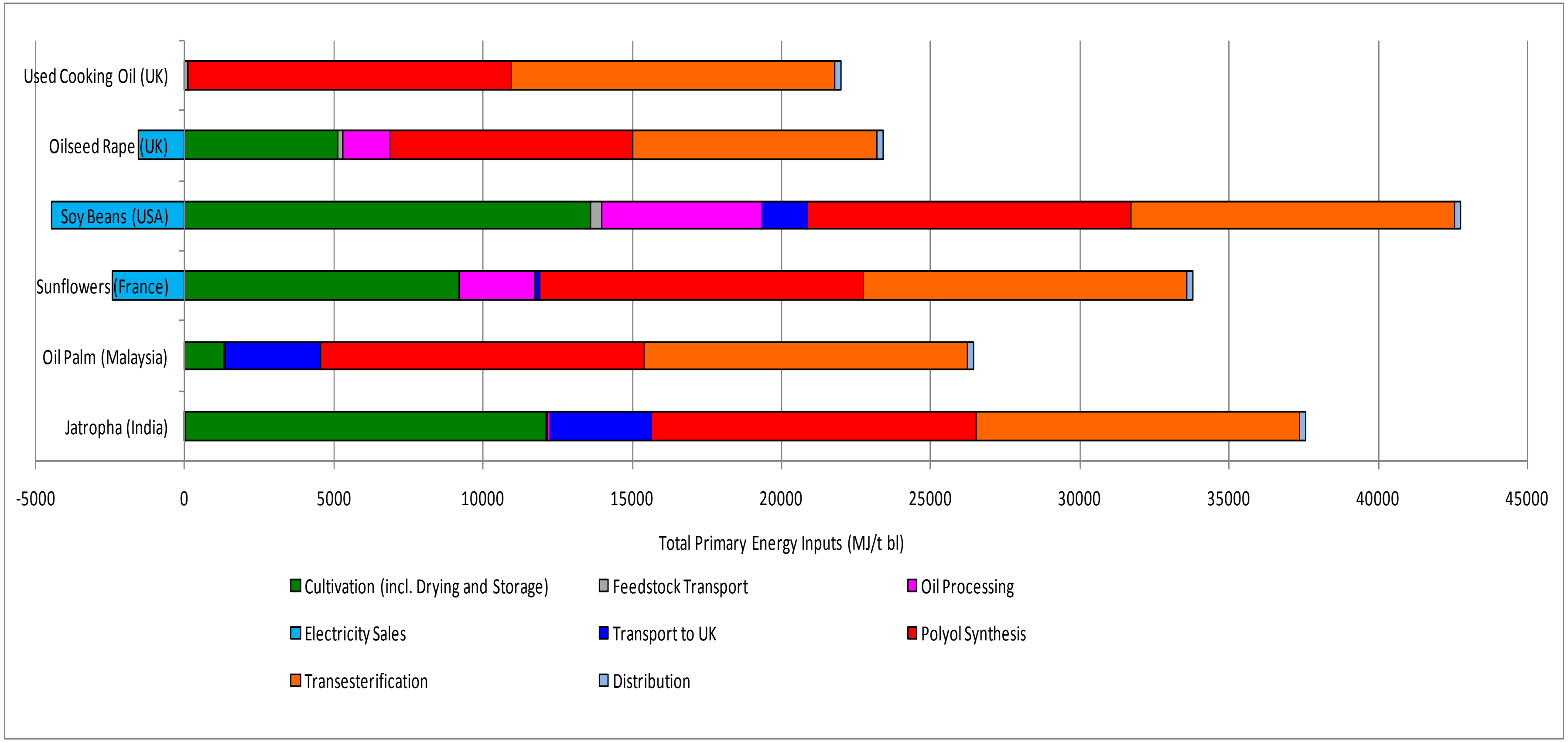


Figure 6 Breakdown of Contributions to Total Primary Energy Inputs for Biolubricant Production



#### 4.2.2 Net Primary Energy Savings

Unit and percentage net primary energy savings are derived in the same way as the equivalent net GHG emissions savings and the same comments apply (see Section 4.1.2). Subsequent results for unit and percentage net primary energy savings are summarised in Tables 14 and 15, respectively. Apparent trends for unit net primary energy savings are very clear in Table 14. Using the same colour coding system as previously adopted, the top and second ranked unit net primary energy savings occur when any of the refined vegetable oils are used in a CHP unit to displace a fuel oil-fired heat (only) with grid electricity, and a natural gas-fired heat (only) boiler with grid electricity. Third and fourth place ranking of unit net primary energy savings are achieved from using biodiesel in a heat (only) boiler to displace a fuel oil-fired heat (only) boiler, and from using biodiesel in a CHP unit to displace a fuel oil-fired heat (only) boiler with grid electricity. The highest unit net primary energy savings of all are achieved with vegetable oil derived from used cooking oil.

The pattern of ranking for percentage net primary energy savings is broadly similar but with some exceptions. Again, maximum primary energy benefits arise for all refined vegetable oils used in a CHP unit to displace either a fuel oil-fired heat (only) boiler or a natural gas-fired heat (only) boiler with, in both instances, grid electricity. Third and fourth place ranking of percentage net primary energy savings for all biodiesel (apart from that derived from oil palms) is used in a heat (only) boiler to displace a fuel oil-fired boiler, or in a CHP unit to displace a fuel oil- or natural gas-fired heat (only) boiler with grid electricity. In the case of oil palms, third and fourth place ranking of percentage net primary energy savings are associated with the use of refined vegetable oil in a CHP unit to displace a natural gas-fired CHP unit, and with the use of refined vegetable oil for electricity (only) generation displacing fuel oil-fired electricity (only) generation and grid electricity.

Specific differences between these comparisons for primary energy and those for GHG emissions are due to a number of considerations. As already mentioned, the GHG emission contributions of N fertiliser manufacture and soil $N_2O$ emissions during the cultivation of biomass feedstocks is not reflected in the primary energy inputs. Additionally, there are differences between the total GHG emissions and total primary energy inputs associated with fuel oil and natural gas. In particular, the total GHG emissions factor for fuel oil (73.28 kg eq. $CO_2$/MJ) is significantly higher than that of natural gas (57.31 kg eq. $CO_2$/MJ); equivalent to a 28% difference (North Energy, 2006). In contrast, the total primary energy factors are very similar for fuel oil (1.073 MJ/MJ) and natural gas (1.050 MJ/MJ); equivalent to a 2% difference (North Energy, 2006). Similar but not quite as significant considerations apply to the comparison of total GHG emissions and total primary energy factors for grid electricity. These relative differences affect the “fossil fuel comparators” which are enough to make modification to the ranking for net GHG emissions savings and net primary energy savings.

NORTH ENERGY

Table 14 Comparison of Unit Net Primary Energy Savings per Unit of Refined Vegetable Oil for Base Cases

| Product | End-Use | Displacing | Net Primary Energy Savings per Unit of Vegetable Oil (MJ/kg ro) | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Used Cooking Oil | Oilseed Rape | Soy Bean | Sun-flowers | Oil Palm | Jatropha |
| Refined Oil | Electricity (Only) | Natural Gas-fired Electricity | 18.8 | 12.5 | 2.9 | 10.3 | 14.3 | 3.1 |
| Refined Oil | Electricity (Only) | Fuel Oil-fired Electricity | 26.8 | 20.2 | 11.6 | 19.1 | 22.4 | 11.8 |
| Refined Oil | Electricity (Only) | Grid Electricity | 26.5 | 19.9 | 11.3 | 18.7 | 22.1 | 11.5 |
| Refined Oil | CHP Heat and Electricity | Natural Gas-fired CHP | 33.3 | 26.5 | 18.9 | 26.3 | 29.1 | 19.7 |
| Refined Oil | CHP Heat and Electricity | Fuel Oil-fired CHP | 34.0 | 27.2 | 19.7 | 27.1 | 29.8 | 20.46 |
| Refined Oil | CHP Heat and Electricity | Natural Gas-fired Heat and Grid Electricity | 47.5 | 40.2 | 34.3 | 41.7 | 43.4 | 35.1 |
| Refined Oil | CHP Heat and Electricity | Fuel Oil-fired Heat and Grid Electricity | 50.6 | 43.2 | 37.7 | 45.1 | 46.6 | 38.5 |
| Refined Oil | Biolubricant | Motor Oil | 18.9 | 16.9 | 9.3 | 12.8 | 14.2 | 2.8 |
| Biodiesel | Heat (Only) | Natural Gas-fired Heat (Only) | 39.9 | 35.3 | 23.7 | 27.0 | 36.8 | 24.2 |
| Biodiesel | Heat (Only) | Fuel Oil-fired Heat (Only) | 44.6 | 40.0 | 28.4 | 31.3 | 41.4 | 28.8 |
| Biodiesel | CHP Heat and Electricity | Natural Gas-fired CHP | 25.9 | 21.2 | 14.4 | 15.1 | 23.1 | 10.5 |
| Biodiesel | CHP Heat and Electricity | Fuel Oil-fired CHP | 26.7 | 21.9 | 15.1 | 15.7 | 23.8 | 11.2 |
| Biodiesel | CHP Heat and Electricity | Natural Gas-fired Heat and Grid Electricity | 40.1 | 35.1 | 28.4 | 27.9 | 36.9 | 24.4 |
| Biodiesel | CHP Heat and Electricity | Fuel Oil-fired Heat and Grid Electricity | 43.2 | 38.1 | 31.5 | 30.7 | 40.0 | 27.4 |
| Biodiesel | Electricity (Only) | Natural Gas-fired Electricity | 11.4 | 7.5 | -4.1 | 1.5 | 8.9 | -2.0 |
| Biodiesel | Electricity (Only) | Fuel Oil-fired Electricity | 19.4 | 15.3 | 3.8 | 8.7 | 16.7 | 5.8 |
| Biodiesel | Electricity (Only) | Grid Electricity | 19.1 | 15.1 | 3.6 | 8.5 | 16.5 | 5.5 |
| Biodiesel | Transport Fuel | Diesel | 31.1 | 26.7 | 15.7 | 19.7 | 27.4 | 15.5 |

Colour Codes for Ranking of Highest Net Primary Energy Savings per Kilogram of Vegetable Oil within Each Pathway for Oil Production

| | |
|---|---|
| First | (magenta) |
| Second | (yellow) |
| Third | (green) |
| Fourth | (grey) |

Table 15 Comparison of Percentage Net Primary Savings for Base Cases

| Product | End-Use | Displacing | Net Primary Energy Savings (%) | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Used Cooking Oil | Oilseed Rape | Soy Bean | Sun-flowers | Oil Palm | Jatropha |
| Refined Oil | Electricity (Only) | Natural Gas-fired Electricity | 99 | 68 | 14 | 50 | 74 | 15 |
| Refined Oil | Electricity (Only) | Fuel Oil-fired Electricity | 99 | 77 | 39 | 65 | 82 | 40 |
| Refined Oil | Electricity (Only) | Grid Electricity | 99 | 77 | 39 | 64 | 82 | 39 |
| Refined Oil | CHP Heat and Electricity | Natural Gas-fired CHP | 99 | 82 | 52 | 72 | 85 | 54 |
| Refined Oil | CHP Heat and Electricity | Fuel Oil-fired CHP | 99 | 82 | 53 | 73 | 86 | 55 |
| Refined Oil | CHP Heat and Electricity | Natural Gas-fired Heat and Grid Electricity | 100 | 87 | 66 | 80 | 90 | 67 |
| Refined Oil | CHP Heat and Electricity | Fuel Oil-fired Heat and Grid Electricity | 100 | 88 | 68 | 82 | 90 | 69 |
| Refined Oil | Biolubricant | Motor Oil | 63 | 56 | 31 | 42 | 47 | 9 |
| Biodiesel | Heat (Only) | Natural Gas-fired Heat (Only) | 82 | 74 | 49 | 61 | 77 | 51 |
| Biodiesel | Heat (Only) | Fuel Oil-fired Heat (Only) | 84 | 77 | 54 | 65 | 79 | 55 |
| Biodiesel | CHP Heat and Electricity | Natural Gas-fired CHP | 77 | 65 | 43 | 50 | 70 | 32 |
| Biodiesel | CHP Heat and Electricity | Fuel Oil-fired CHP | 78 | 65 | 44 | 51 | 71 | 33 |
| Biodiesel | CHP Heat and Electricity | Natural Gas-fired Heat and Grid Electricity | 84 | 75 | 60 | 65 | 79 | 52 |
| Biodiesel | CHP Heat and Electricity | Fuel Oil-fired Heat and Grid Electricity | 85 | 77 | 63 | 67 | 80 | 55 |
| Biodiesel | Electricity (Only) | Natural Gas-fired Electricity | 60 | 40 | -22 | 9 | 48 | -11 |
| Biodiesel | Electricity (Only) | Fuel Oil-fired Electricity | 72 | 58 | 14 | 36 | 64 | 22 |
| Biodiesel | Electricity (Only) | Grid Electricity | 72 | 58 | 13 | 35 | 63 | 21 |
| Biodiesel | Transport Fuel | Diesel | 80 | 70 | 41 | 56 | 72 | 41 |

Colour Codes for Ranking of Highest Net Primary Energy Savings within Each Pathway for Oil Production

| | |
|---|---|
| First | (magenta) |
| Second | (yellow) |
| Third | (green) |
| Fourth | (grey) |

# 5 SENSITIVITIES

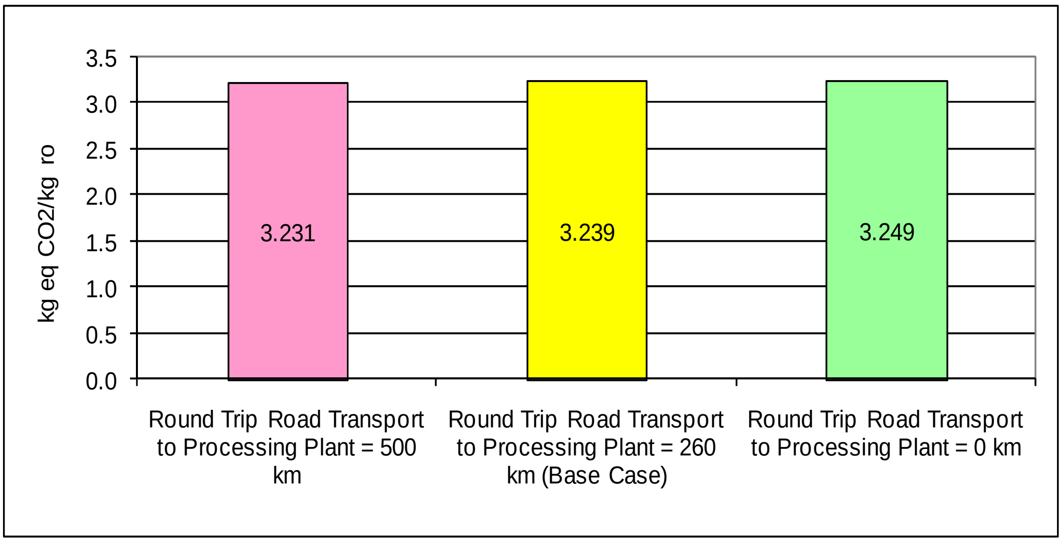
## 5.1 Sensitivity Analysis

The nature of the workbooks developed for this study provides considerable scope for sensitivity analysis. However, not all possible sensitivities are examined and reported here as there are too many and their inclusion is likely to be confusing. Instead, it was decided to concentrate on the main sensitivities of the combinations which resulted in the top two ranking unit net total GHG emissions savings reported in Table 9. These concern the use of refined vegetable oils in CHP units to displace a fuel oil-fired boiler with grid electricity, and the use of biodiesel in a heat (only) boiler to displace a fuel oil-fired heat (only) boiler. The effects of the main sensitivities on maximum unit net GHG emissions savings are examined for each biomass feedstock in turn.

## 5.2 Refined Vegetable Oil

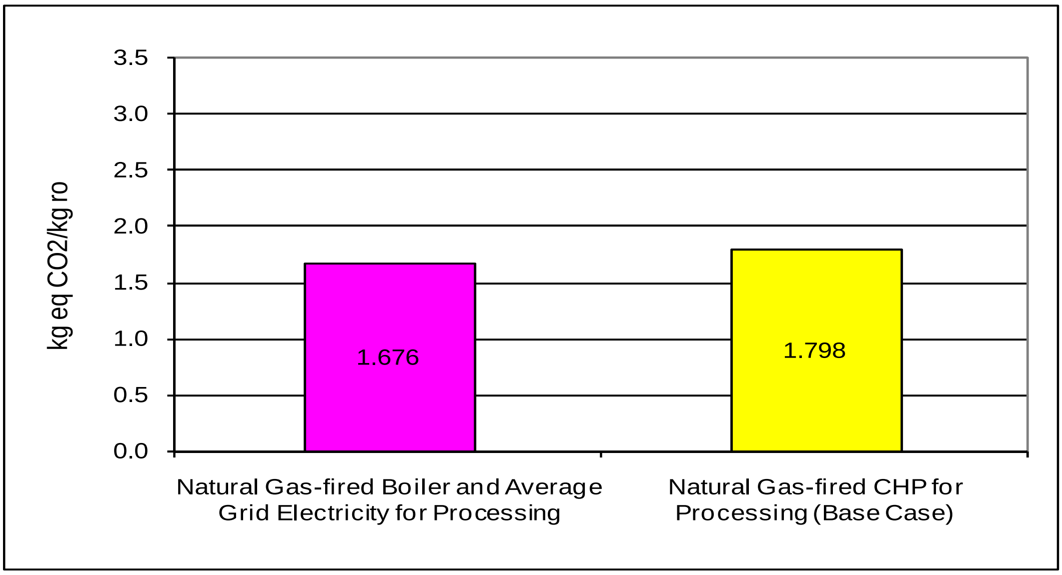
The main sensitivities affecting the production of refined vegetable oil from used cooking oil in the UK are limited due to the relative simplicity of processing this particular biomass feedstock. The most important variable is the round trip road transport distance for the collection of used cooking oil and the effects of this are demonstrated in Figure 7. This shows that unit net GHG emissions savings are not very sensitive to the transport distance. In particular, a 92% increase in the round trip distance from a Base Case value of 260 km reduces net savings by less than 1%. Eliminating road transport completely has little significant impact on savings.

Figure 7 Sensitivities for Used Cooking Oil: Refined Vegetable Oil in CHP Plant Displacing Fuel Oil-fired Heat (only) Boiler and Average Grid Electricity



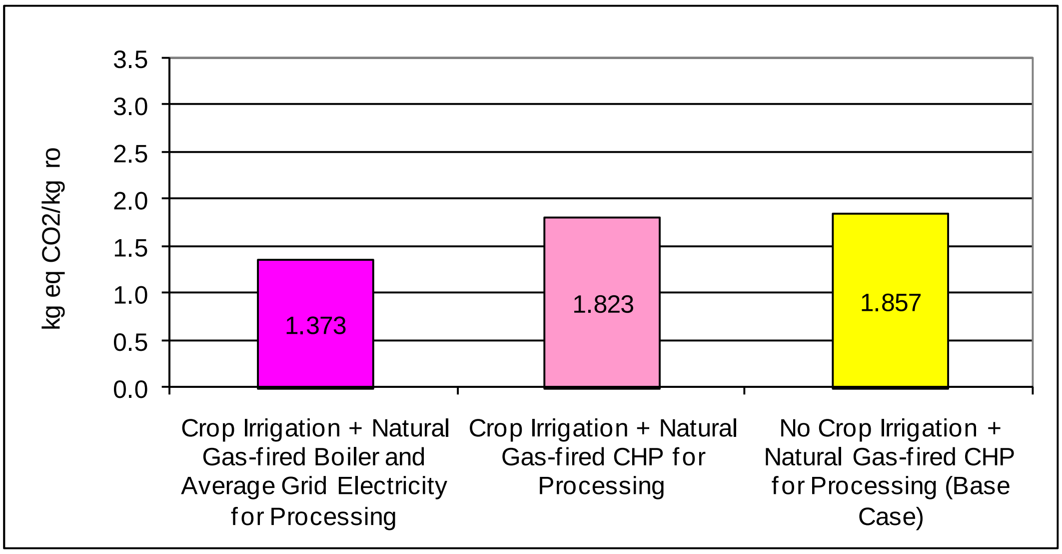

In the case of refined vegetable oil produced from oilseed rape in the UK, the most prominent sensitivity is the choice of source for heat and electricity used in oil extraction and refining. The Base Case assumes that a natural gas-fired CHP unit will be used for this processing. However, as shown in Figure 8, switching to a natural gas-fired heat (only) boiler and grid electricity would produce a moderate reduction in unit net GHG savings of 7%.

Figure 8 Sensitivities for Oilseed Rape: Refined Vegetable Oil in CHP Plant Displacing Fuel Oil-fired Heat (only) Boiler and Average Grid Electricity



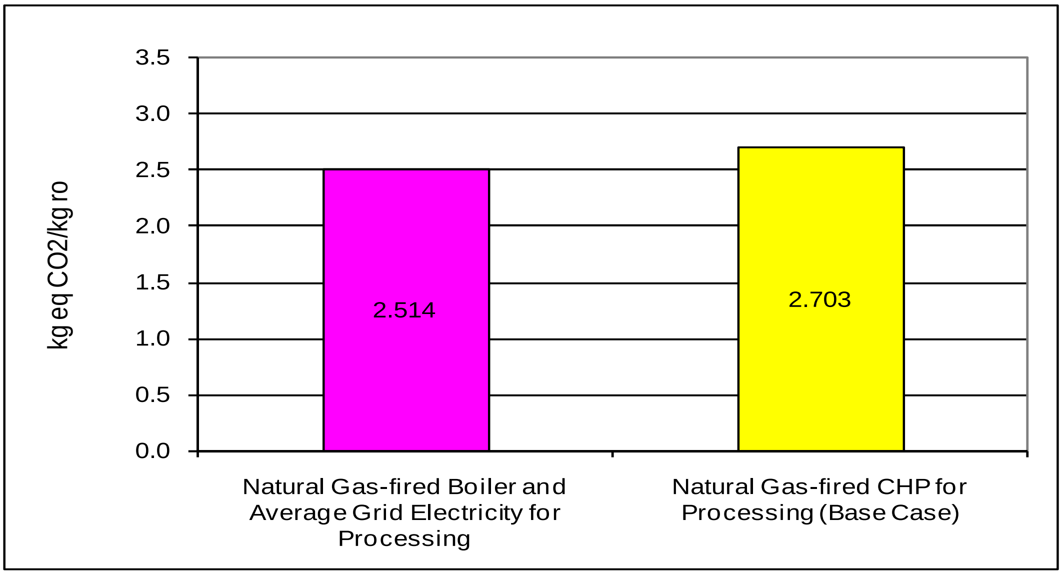

Both the choice of the source of energy for processing and use of irrigation in cultivation are relevant sensitivities for refined vegetable oil produced from soy beans in the USA. The Base Case assumes that a natural gas-fired CHP unit is used for processing and that the crop is not irrigated. As indicated in Figure 9, the use of irrigation in the USA, which would use diesel-powered water pumps, reduces unit net GHG emissions savings by 2%. If processing is also switched from a natural gas-fired CHP unit to a natural gas-fired boiler with US grid electricity, to overall reduction in unit net GHG emissions savings is a more significant 26%.

Figure 9 Sensitivities for Soy Beans: Refined Vegetable Oil in CHP Plant Displacing Fuel Oil-fired Heat (only) Boiler and Average Grid Electricity



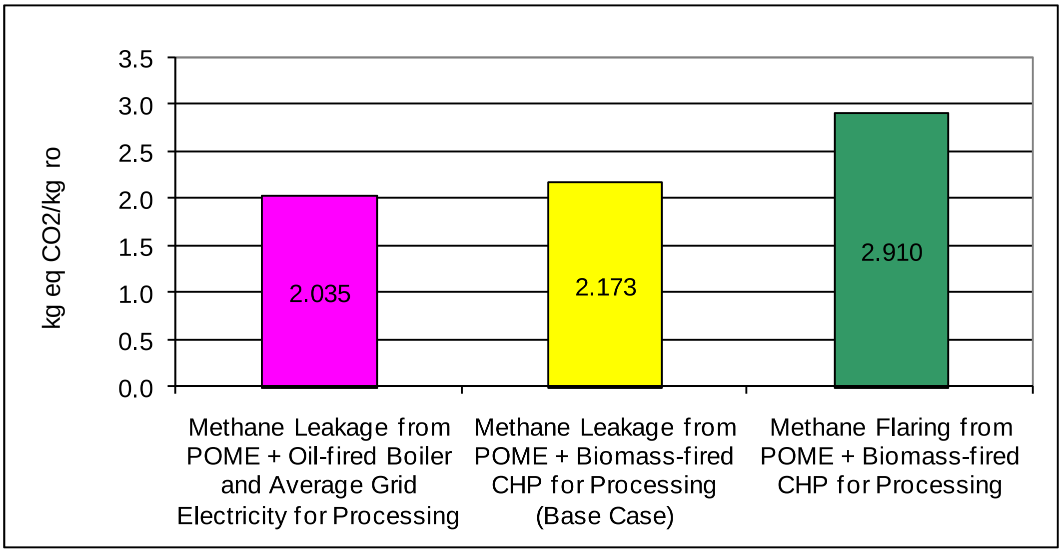
In the case of producing refined vegetable oil from sunflowers in France, the choice of the source of processing energy is also the main sensitivity. However, Figure 10 demonstrates that the switch from natural gas-fired CHP to a natural gas-fired boiler and French grid electricity only reduces unit net GHG emissions savings by a moderate 7%.

Figure 10 Sensitivities for Sunflowers: Refined Vegetable Oil in CHP Plant Displacing Fuel Oil-fired Heat (only) Boiler and Average Grid Electricity



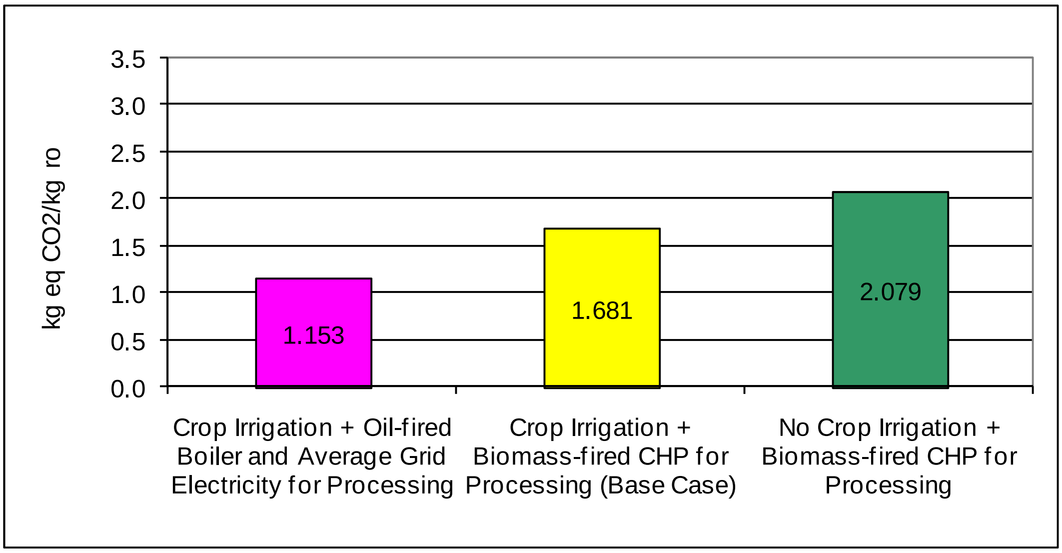

Two important sensitivities can affect the unit net GHG emissions savings of refined vegetable oil derived from oil palms in Malaysia. One major sensitivity is whether $CH_4$ is allowed to leak from the palm oil mill effluent (POME) or whether it is collected and flared (to biogenic $CO_2$). The other major sensitivity is the choice of the source of energy for processing; the main options being use of empty fruit bunches and palm kernel fibre in a biomass-fired CHP unit or an oil-fired heat (only) boiler with Malaysian grid electricity. The Base Case assumes $CH_4$ leakage from POME with the use of a biomass-fired CHP unit. As shown in Figure 11, if the methane from POME is flared, unit net GHG emissions savings can increase by 34%. Alternatively, if the source of energy for processing is switched to an oil-fired heat (only) boiler with imported grid electricity, the unit net GHG emissions savings decrease by a moderate 6%.

Figure 11 Sensitivities for Oil Palms: Refined Vegetable Oil in CHP Plant Displacing Fuel Oil-fired Heat (only) Boiler and Average Grid Electricity




Both the choice of the source of energy for processing and whether irrigation is used in cultivation are important sensitivities for the commercial production of refined vegetable oil from jatropha in India. In the Base Case, it is assumed that jatropha prunings are used in a biomass-fired CHP plant for the heat and electricity required in oil extraction and refining. It is also assumed that the crop has to be irrigated using diesel-powered water pumps. As illustrated in Figure 12, avoiding irrigation increases the unit net GHG emissions savings by a significant 24%. In contrast, switching from a biomass-fired CHP unit to an oil-fired heat (only) boiler with Indian grid electricity for processing decreases these savings by a notable 31%.

Figure 12 Sensitivities for Jatropha: Refined Vegetable Oil in CHP Unit Displacing Fuel Oil-fired Heat (only) Boiler and Average Grid Electricity



The choice of GHG emissions calculation methodologies can also be an important sensitivity. In order to investigate this sensitivity in a systematic manner, various options were examined. Most of those chosen were intended to reflect the main methodologies currently available or adopted within relevant tools; the EC RED, the RFA Technical Guidance, PAS 2050 and $BEAT_2$. The set up of specific input variables in the workbooks to simulate these and other methodologies in this sensitivity analysis are summarised in Table 16. The effects of these simulated methodologies on unit net GHG emissions savings when refined vegetable oil is used in a CHP unit to displace a fuel oil-fired heat (only) boiler with grid electricity are investigated separately for each biomass feedstock. In all instances, the Base Case represents the application of the EC RED (with energy content allocation, replacement generation as a credit for surplus electricity from CHP units used in processing, and plant and equipment excluded from calculations)

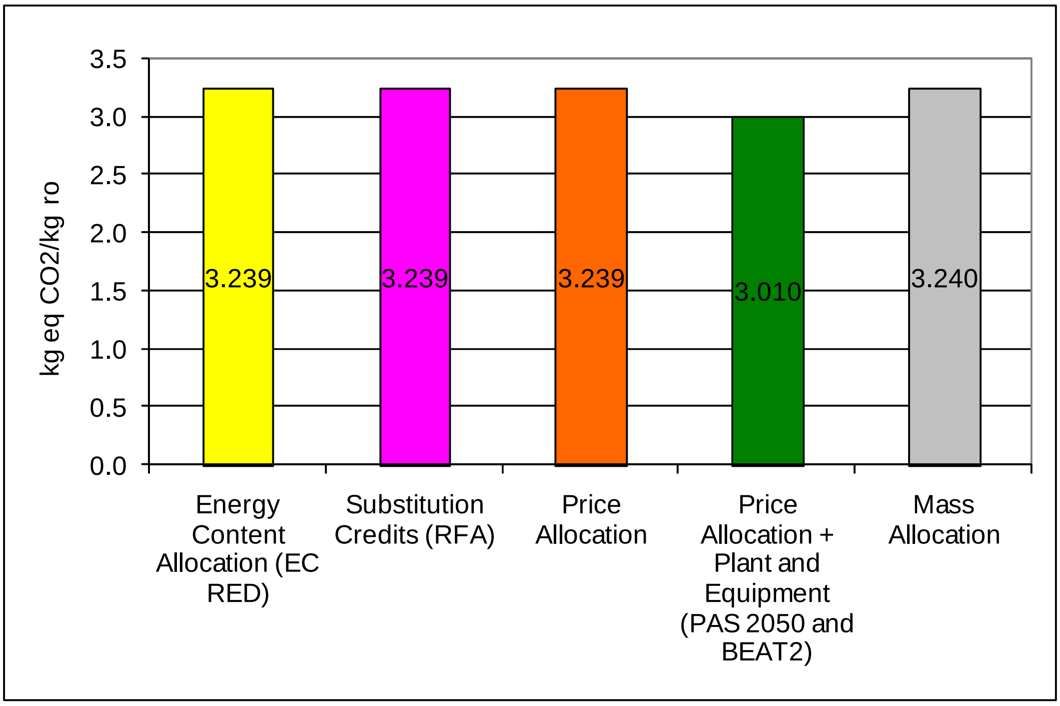
Table 16 Specified Input Variables for Simulation of GHG Emissions Calculation Methodologies

| Co-Product Allocation | Credit for Surplus Electricity from CHP Used in Processing | Plant and Equipment | Simulated GHG Emission Calculation Methodology |
|---|---|---|---|
| Energy Content | Replacement Generation | Excluded | EC RED |
| Substitution Credits | Gross Grid or Marginal Generation (UK only) | Excluded | RFA Technical Guidance |
| Price | Gross Grid | Excluded | None Specific |
| Price | Gross Grid | Included | PAS 2050 |
| Price | Net Grid | Included | $BEAT_2$ |
| Mass | Gross Grid | Excluded | None Specific |

Figure 13 demonstrates only moderate effects of methodologies on savings for refined vegetable oil derived from used cooking oil. There is little difference between the results generated using the EC RED, the RFA Technical Guidance, and price and mass allocation, provided that the effects of plant and equipment are excluded. However, the inclusion of plant and equipment in GHG emissions calculations with price allocation, for the simulation of the PAS 2050 and $BEAT_2$ methodologies, produces a slight reduction of 7% in savings. In general, the results for refined vegetable oil production from used cooking oil are quite insensitive to the GHG emissions calculation methodology because no by-products are generated by this process; processing is assumed to use a natural gas-fired heat (only) boiler with grid electricity so that surplus electricity from a CHP unit is not a consideration; and processing is relatively simple so that little plant and equipment is required.

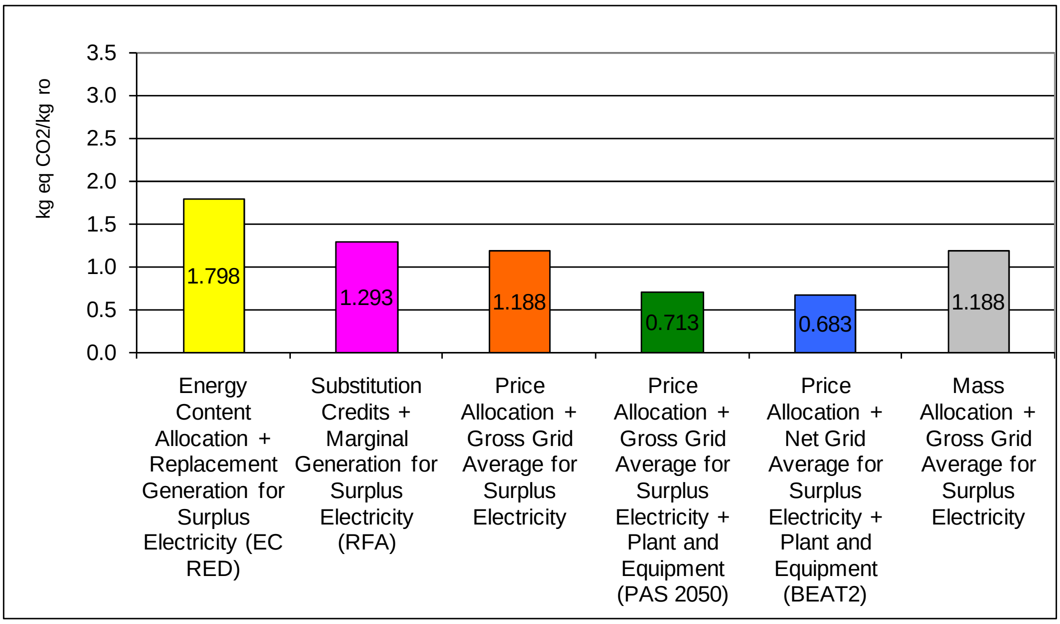
In contrast, all the other vegetable oils considered in this study are much more sensitive to the choice of GHG emissions calculation methodology. Figure 14 shows the effect of methodologies on savings for refined vegetable oil produced from UK oilseed rape. The Base Case, which simulates the EC RED, generates the highest savings of

Figure 13 Effect of GHG Calculation Methodologies for Used Cooking Oil: Refined Vegetable Oil in CHP Unit Displacing Fuel Oil-fired Heat (only) Boiler and Average Grid Electricity



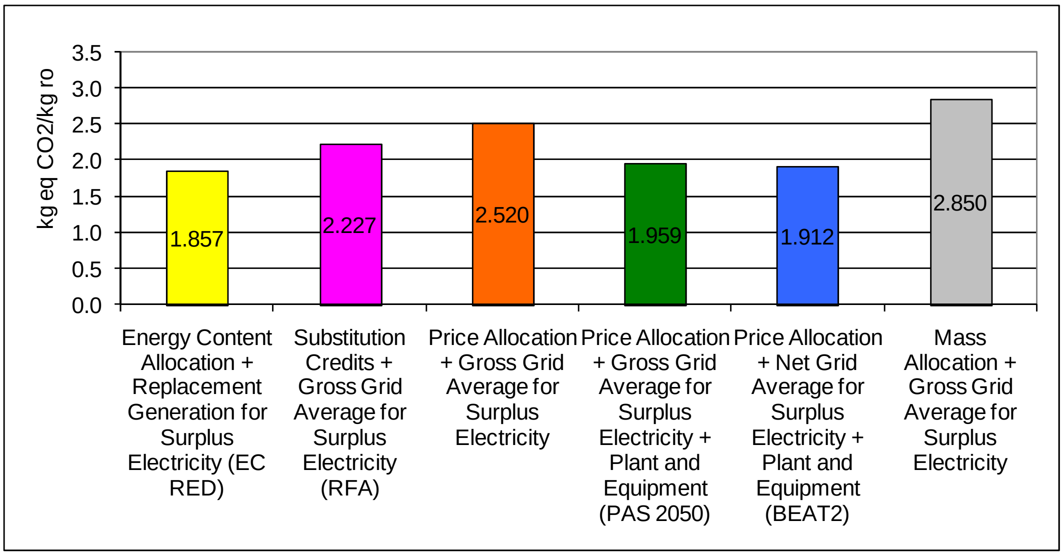

the methodologies considered. The largest reduction of 21% in savings occurs when the methodology used in $BEAT_2$ is adopted. This occurs mainly because of the large amount of energy contained (energy content x amount) in the by-product (rape meal) relative to that in the refined vegetable oil compared with the relative values (price x amount) of these co-products.

Figure 14 Effect of GHG Calculation Methodologies for Oilseed Rape: Refined Vegetable Oil in CHP Unit Displacing Fuel Oil-fired Heat (only) Boiler and Average Grid Electricity



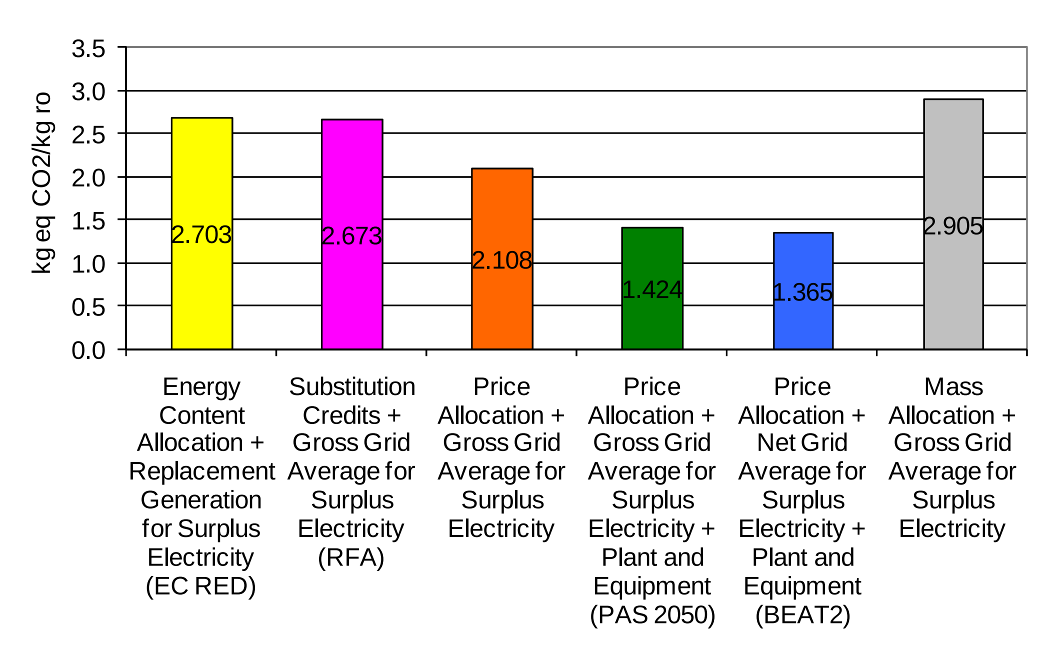
The effect of GHG emissions calculation methodologies on the savings from refined vegetable oil produced from US soy beans is less pronounced and results in different outcome. As shown in Figure 15, the EC RED methodology reflected in the Base Case produces the lowest unit net GHG emissions savings. Considerably higher savings, with an increase of 41% above the Base Case and the EC RED, can be obtained with price allocation, excluding plant and equipment. PAS 2050 and $BEAT_2$ methodologies generate much smaller increases in savings of 5% and 2%, respectively. These differences are largely due to the relative energy contents and prices of co-products (refined vegetable oil and soy meal) incorporated into the workbooks.

Figure 15 Effect of GHG Calculation Methodologies for Soy Beans: Refined Vegetable Oil in CHP Unit Displacing Fuel Oil-fired Heat (only) Boiler and Average Grid Electricity




In the case of refined vegetable oil derived from French sunflowers, another pattern of sensitivities emerges as shown in Figure 16. The highest unit net GHG emissions savings occur when co-products (refined vegetable oil and sunflower meal) are allocated by mass (with credit for surplus electricity from the CHP unit used in processing based on gross grid electricity, and plant and equipment excluded). This is 7% higher than the savings estimated using the EC RED in the Base Case. Simulation of the effects of the PAS 2050 and $BEAT_2$ methodologies reduces savings by 47% and 50%, respectively. Although differences in the relative values of the energy content, mass and price are partly responsible for these changes in savings, the impact of including plant and equipment in the GHG emissions calculation is more influential. This is mainly due to the machinery-intensive nature of crop cultivation which is apparent by comparing savings based on price allocation (using gross grid electricity as the credit for surplus CHP electricity and excluding or including plant and equipment in the calculations). In addition to refined vegetable oil from French sunflowers (Figure 16), this is the case for refined vegetable oil from UK oilseed rape (Figure 14) and from US soy beans (Figure 15).

Figure 16 Effect of GHG Calculation Methodologies for Sunflowers: Refined Vegetable Oil in CHP Unit Displacing Fuel Oil-fired Heat (only) Boiler and Average Grid Electricity




As can be seen in Figure 17, the effect of plant and equipment is less prominent for refined vegetable oil production from oil palms because of cultivation practices. There is a marginal reduction in savings under the PAS 2050 and $BEAT_2$ methodologies of 16% and 17%, respectively, compared with the Base Case result which adopts the EC RED. Relative energy content, prices and mass for the co-products (refined vegetable oil, press cake and palm stearin) are not significantly different. It will be noted from Figure 17 that the effect of applying the RFA Technical Guidance is not investigated. This is due to the fact that actual substitution credits for the by-products are not available.

The effect of GHG emissions calculations methodologies on the savings from refined vegetable oil derived from jatropha is probably the most dramatic, as demonstrated in Figure 18. This shows that savings are substantially reduced from those under the EC RED, represented in the Base Case, when any form of price allocation is applied. Price allocation excluding plant and equipment from the calculations causes a 77% decrease in savings. Savings are almost eliminated when the PAS 2050 and $BEAT_2$ methodologies are adopted, with reductions of 94% in both instances. This is because the assumed relative prices of by-products (press cake and hulls) are low or zero (respectively) to the price of refined vegetable oil, in contrast to much higher relative energy contents, as used in the EC RED and reflected in the Base Case results. As with the sensitivity analysis results for refined vegetable oil derived from oil palms, the effect of applying the RFA Technical Guidance was not examined in Figure 18 because no substitution credits have been published for these by-products.

Figure 17 Effect of GHG Calculation Methodologies for Oil Palms: Refined Vegetable Oil in CHP Unit Displacing Fuel Oil-fired Heat (only) Boiler and Average Grid Electricity

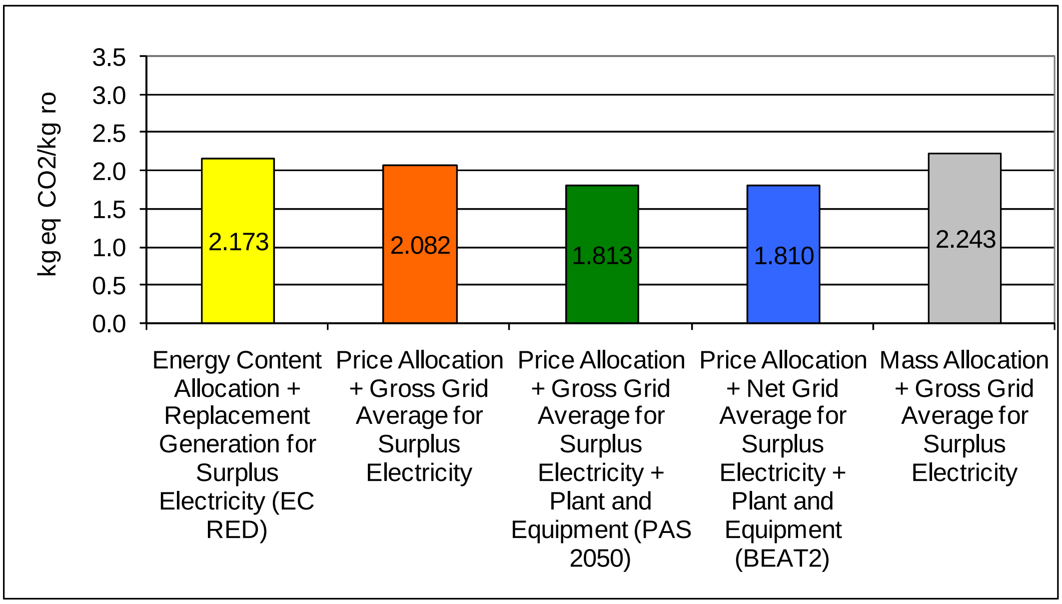
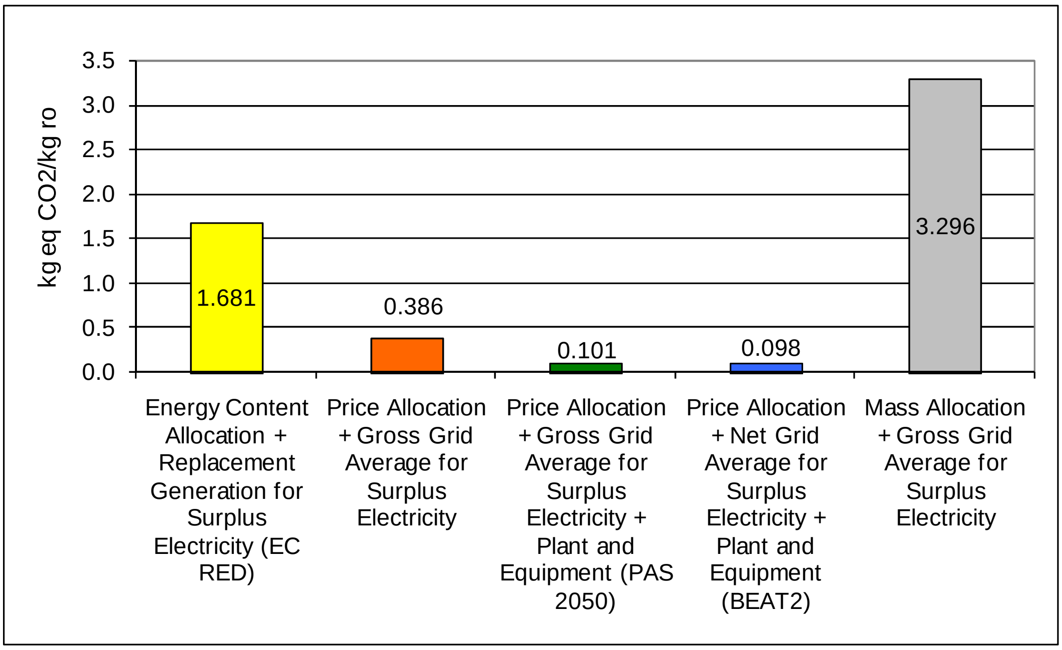


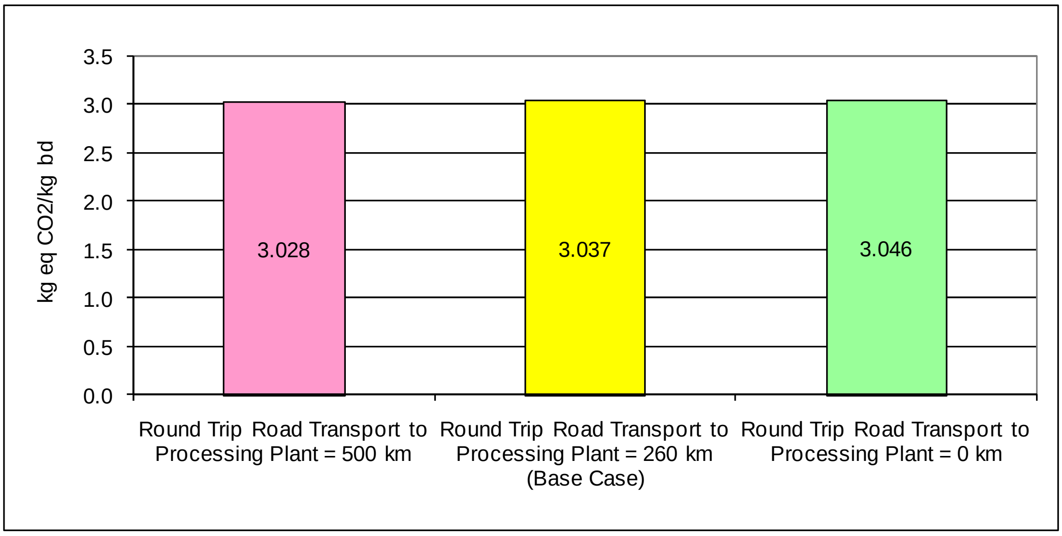

Figure 18 Effect of GHG Calculation Methodologies for Jatropha: Refined Vegetable Oil in CHP Unit Displacing Fuel Oil-fired Heat (only) Boiler and Average Grid Electricity



### 5.3 Biodiesel

Sensitivity analysis for the unit net GHG emissions savings associated with the use of biodiesel in a heat (only) boiler displacing a fuel oil-fired heat (only) boiler produces similar results to those for refined vegetable oil. Figure 19 again demonstrates that the savings for refined vegetable oil from used cooking oil in the UK is rather insensitive to variations in the round trip road transport distance for biomass feedstock collection.

Figure 19 Sensitivities for Used Cooking Oil: Biodiesel in Heat (only) Boiler Displacing Fuel Oil-fired Heat (only) Boiler




A switch from a natural gas-fired CHP unit for heat and electricity to a natural gas-fired heat (only) boiler and grid electricity used in oil extraction, refining and esterification of UK oilseed rape causes a moderate 6% reduction in savings, as shown in Figure 20.

Figure 20 Sensitivities for Oilseed Rape: Biodiesel in Heat (only) Boiler Displacing Fuel Oil-fired Heat (only) Boiler

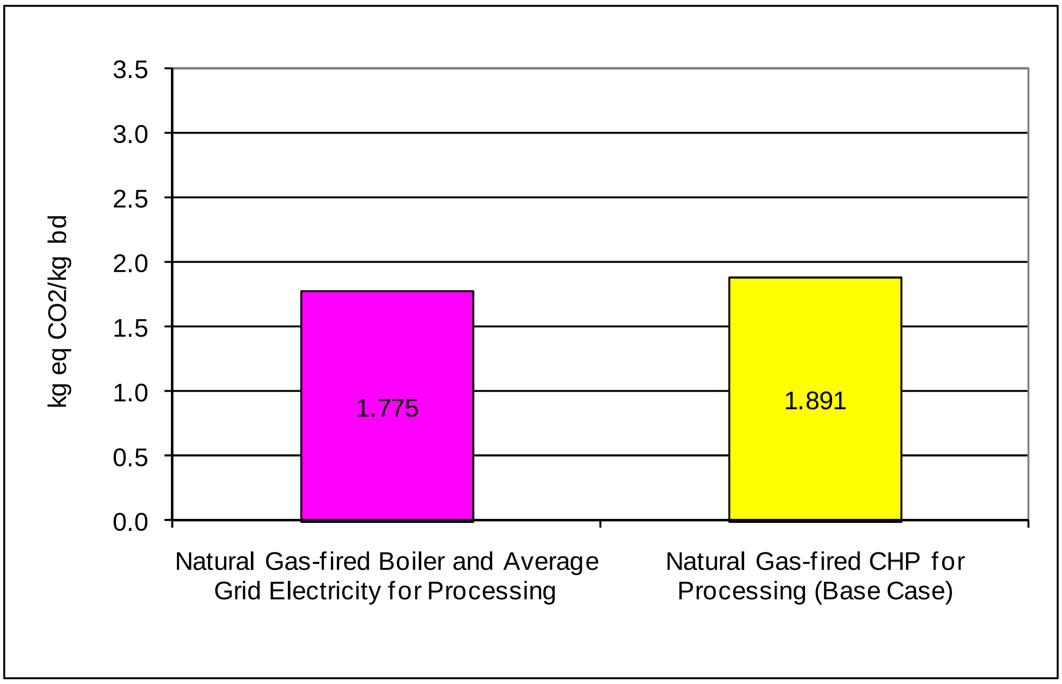
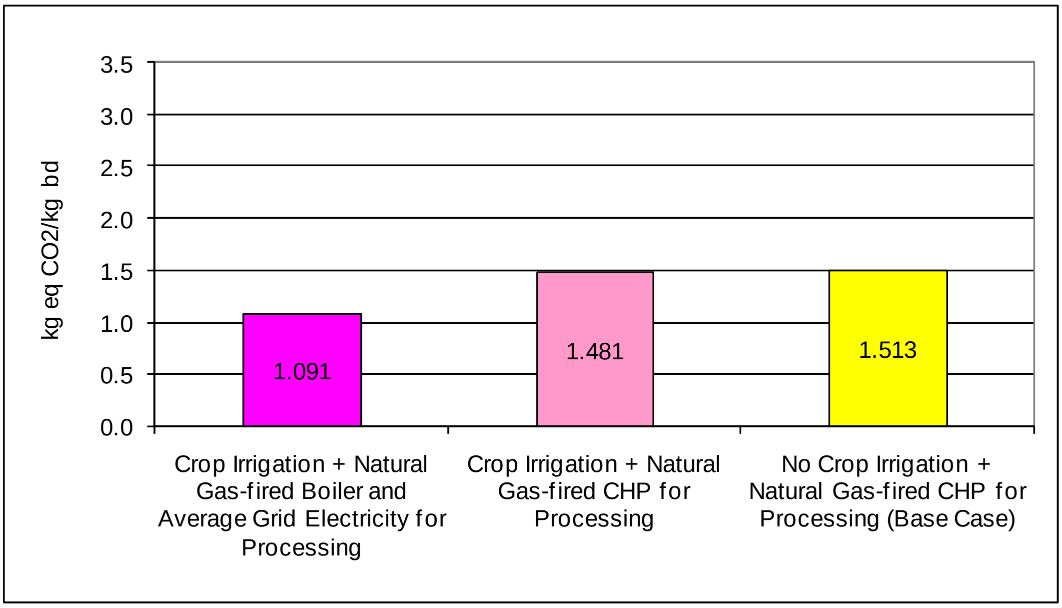


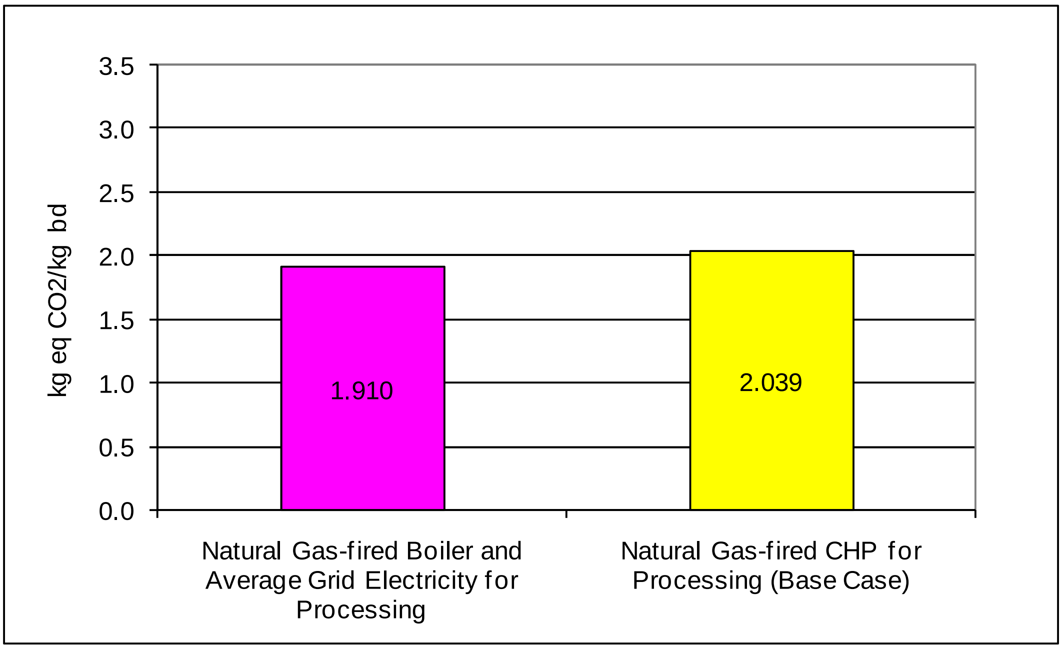
Figure 21 indicates that the use of crop irrigation in US soy bean cultivation results in a small decrease of 2% in unit net GHG emissions savings for biodiesel. However, combined with a switch from a natural gas-fired CHP unit for oil extraction and refining to the use of a natural gas-fired heat (only) boiler and grid electricity produces a larger reduction in savings of 28%.

Figure 21 Sensitivities for Soy Beans: Biodiesel in Heat (only) Boiler Displacing Fuel Oil-fired Heat (only) Boiler



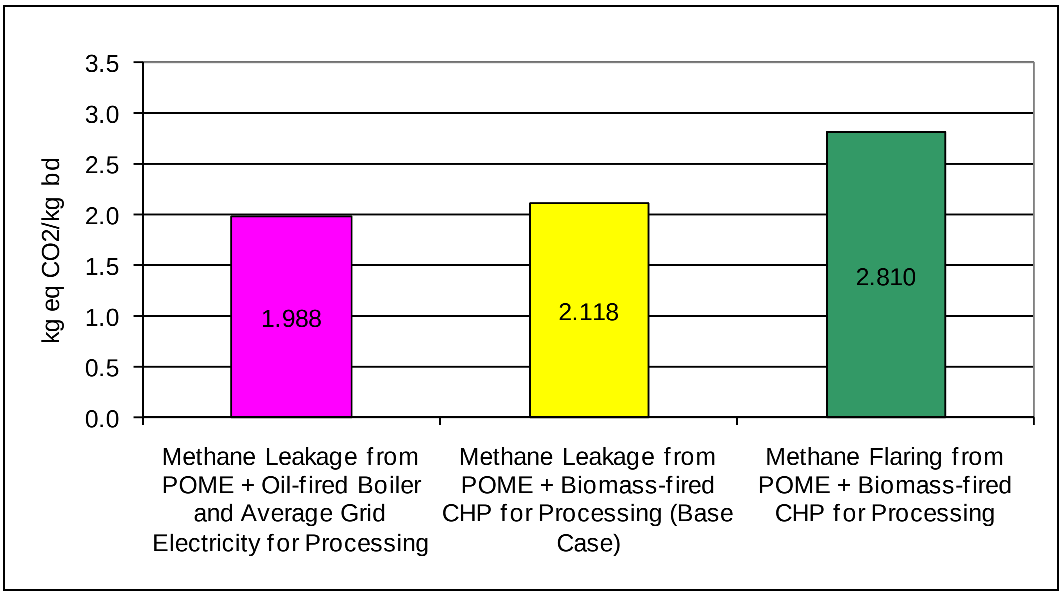

As illustrated in Figure 22, only a small 6% reduction in the savings associated with biodiesel from French sunflowers occurs when processing energy for oil extraction and refining is switched from a natural gas-fired CHP unit to a natural gas-fired heat (only) boiler and grid electricity.

Figure 22 Sensitivities for Sunflowers: Biodiesel in Heat (only) Boiler Displacing Fuel Oil-fired Heat (only) Boiler



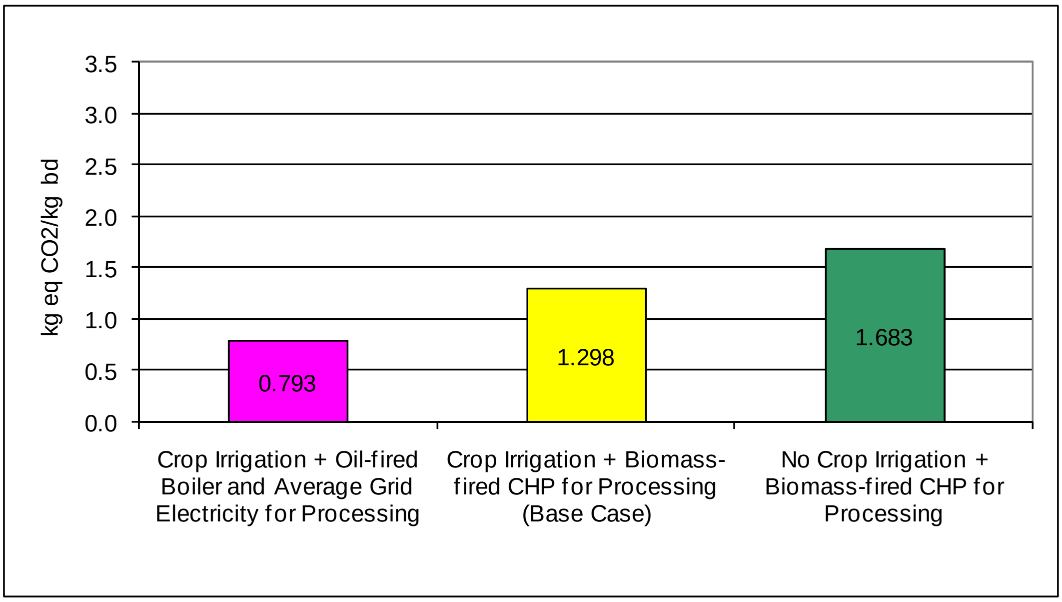
The effect of capturing and flaring $CH_4$ from POME is apparent for biodiesel derived from Malaysian oil palms in Figure 23. This results in a significant 33% increase in savings over the Base Case which assumes $CH_4$ leakage into the atmosphere from POME. In contrast, a switch from a biomass-fired CHP unit for oil extraction and refining to an oil-fired heat (only) boiler and grid electricity only decreases savings by 6%.

Figure 23 Sensitivities for Oil Palms: Biodiesel in Heat (only) Boiler Displacing Fuel Oil-fired Heat (only) Boiler



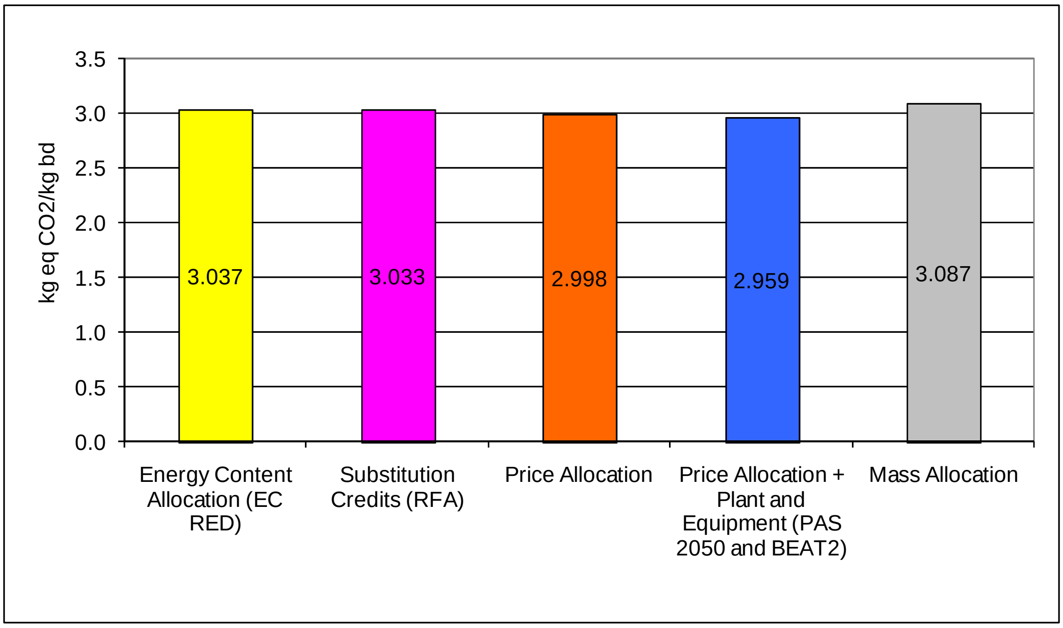

A reasonably significant increase of 30% in savings over that for the Base Case result can be achieved by avoiding the irrigation of Indian jatropha used in biodiesel production is indicated in Figure 24. However, if irrigation is still required and oil extraction and refining energy is provided by an oil-fired heat (only) boiler with grid electricity instead of a biomass-fired CHP unit, then a 39% decrease in savings occurs.

Figure 24 Sensitivities for Jatropha: Biodiesel in Heat (only) Boiler Displacing Fuel Oil-fired Heat (only) Boiler



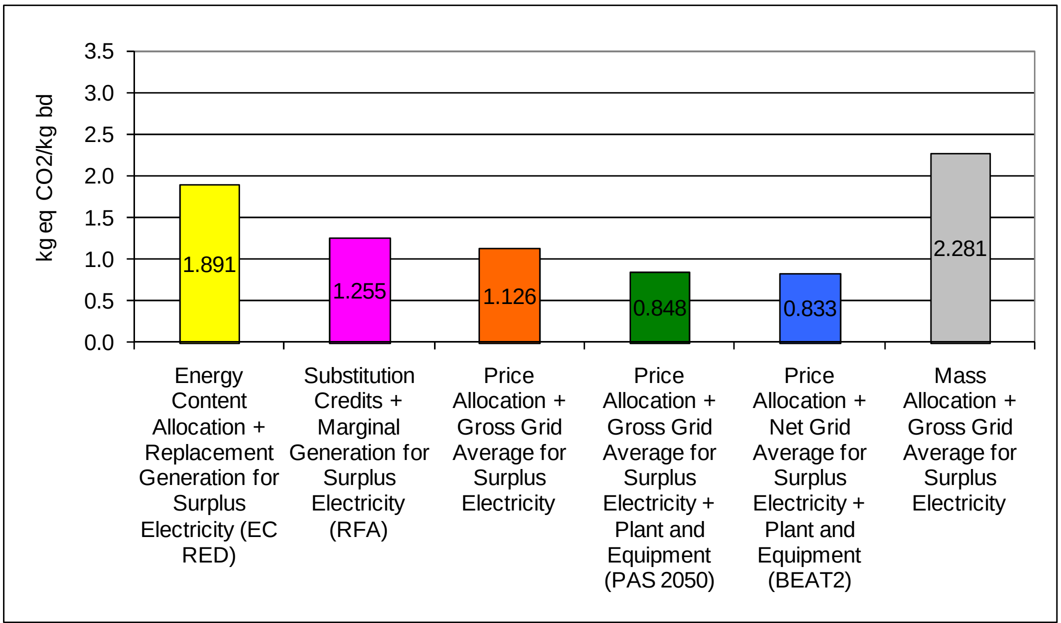
The effect of GHG emissions calculation methodologies on biodiesel used in a heat (only) boiler displacing a fuel oil-fired heat (only) boiler can be investigated with the workbooks by applying the same variable setting summarised earlier in Table 16. Only small changes in savings are seen in Figure 25 for biodiesel produced from UK used cooking oil when different methodologies are applied. These insignificant changes are mainly caused by variations in co-product allocation as it relates to a relatively small amount of glycerine generated during esterification.

Figure 25 Effects of Calculation Methodologies for Used Cooking Oil: Biodiesel in Heat (only) Boiler Displacing Fuel Oil-fired Heat (only) Boiler



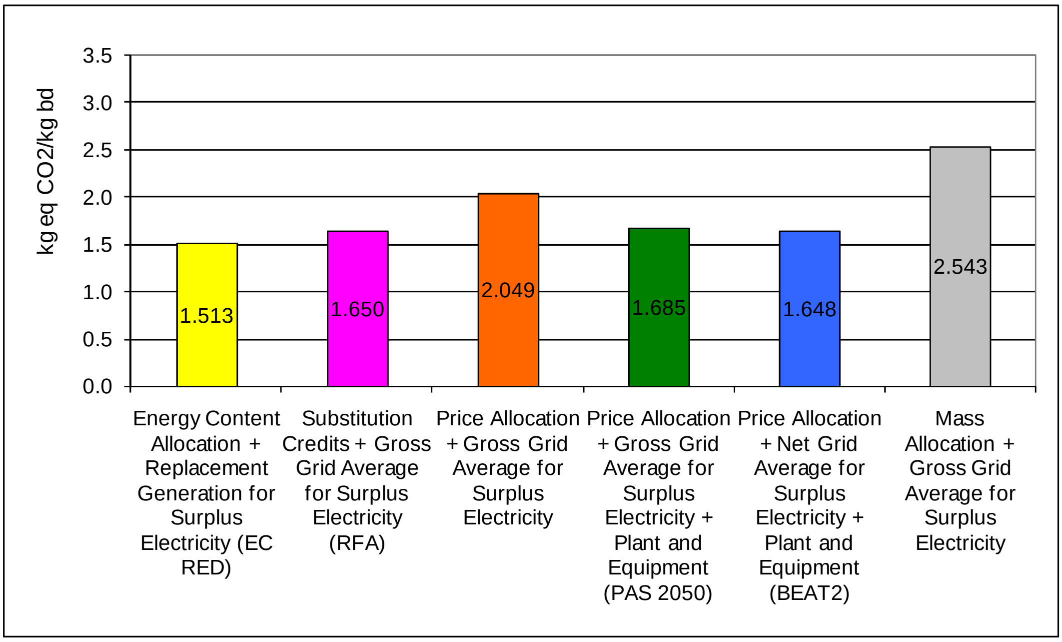

As with refined vegetable oil, savings from biodiesel obtained from UK oilseed rape are substantially affected by changes in GHG emissions calculation methodologies. Figure 26 demonstrates that application of EC RED, reflected in the Base Case, results in the highest unit net GHG emissions savings. Price allocation, particularly including plant and equipment in GHG emissions calculations, thereby representing the PAS 2050 and $BEAT_2$ methodologies, produces the lowest savings which are reductions of 55% and 56%, respectively, on the result with the EC RED. The additional allocation to glycerine generated from esterification simply reinforces the trend already established for the production of refined vegetable oil.

Figure 26 Effect of Calculation Methodologies for Oilseed Rape: Biodiesel in Heat (only) Boiler Displacing Fuel Oil-fired Heat (only) Boiler



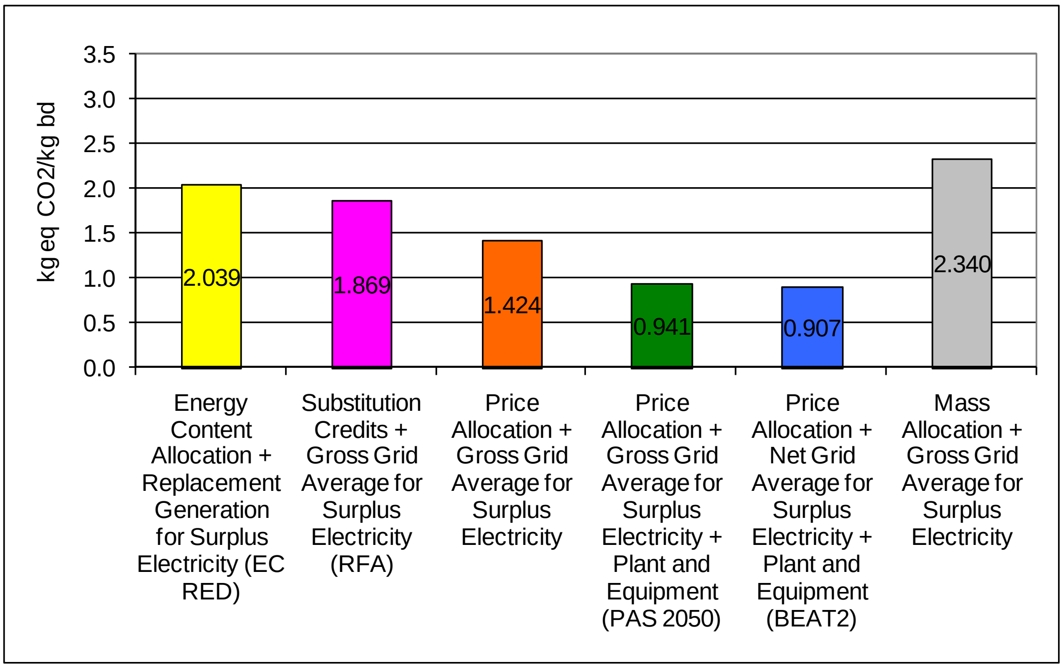

Similarly, Figure 27 for biodiesel derived from US soy beans shows the earlier effect of GHG emissions calculation methodologies on savings from refined vegetable oil. A 35% increase in savings occurs when plant and equipment are excluded and price allocation is used instead of the EC RED of the Base Case. However, this increase is moderated when plant and equipment is included in the calculations, with only a 11% increase for the PAS 2050 methodology and a 9% increase for the $BEAT_2$ methodology.

Figure 27 Effect of Calculation Methodologies for Soy Beans: Biodiesel in Heat (only) Boiler Displacing Fuel Oil-fired Heat (only) Boiler



The application of price allocation, and excluding plant and equipment in calculations, reduces unit net GHG emissions savings from biodiesel produced from French sunflowers by 30% relative to the Base Case reflecting the EC RED in Figure 28. Including plant and equipment decreases savings by 54% and 56%, respectively, when the PAS 2050 and $BEAT_2$ methodologies are adopted. Again, the intensive use of agricultural machinery, with relatively short working lives, has a significant effect for sunflower cultivation. This trend is also apparent for the cultivation of UK oilseed rape (Figure 26) and, to a lesser extent, the cultivation of US soy beans (Figure 27).

Figure 28 Effect of Calculation Methodologies for Sunflowers: Biodiesel in Heat (only) Boiler Displacing Fuel Oil-fired Heat (only) Boiler




Only relatively minor changes in savings with changes in GHG emissions calculation methodologies are apparent in Figure 29 for biodiesel derived from Malaysian oil palms. As with refined vegetable oil previously, there are no significant differences in the relative energy content, prices and mass for the co-products (refined vegetable oil, press cake and palm stearin). Again, the effect of applying the RFA Technical Guidance has not been investigated because no published substitution credits for the by-products are available.

Much more significant effects of changes in GHG emissions calculation methodologies can be seen in Figure 30 for biodiesel produced from Indian jatropha. On this occasion, the impact of applying price allocation (excluding or including plant and equipment in the calculations) is very important since this actually reverses the savings. This means that the use of biodiesel from jatropha for heat (only) generation actually releases more total GHG emissions than fuel oil-fired heat (only) production.

Figure 29 Effects of Calculation Methodologies Oil Palms: Biodiesel in Heat (only) Boiler Displacing Fuel Oil-fired Heat (only) Boiler

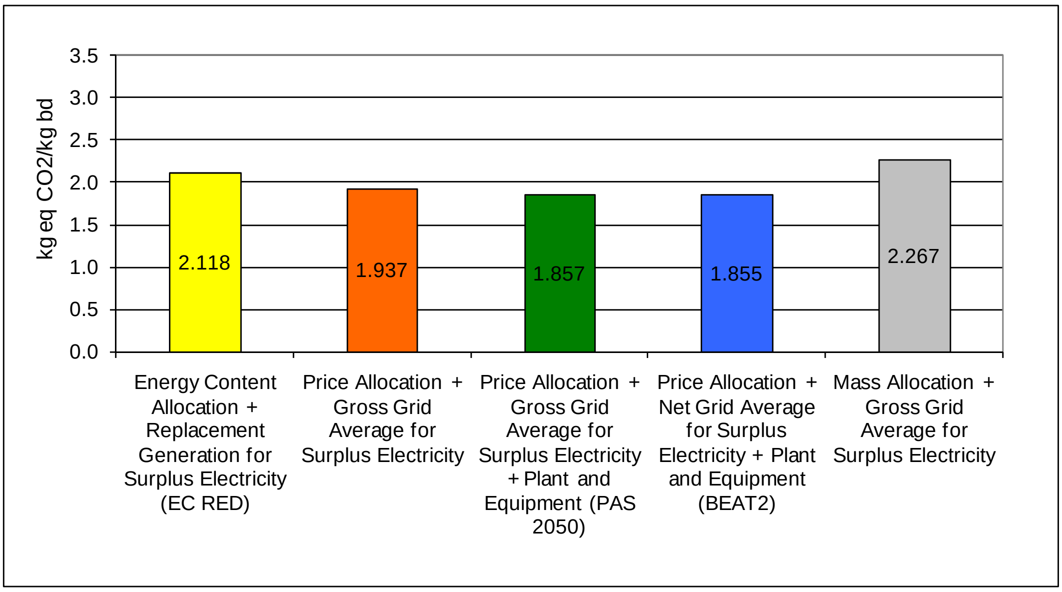
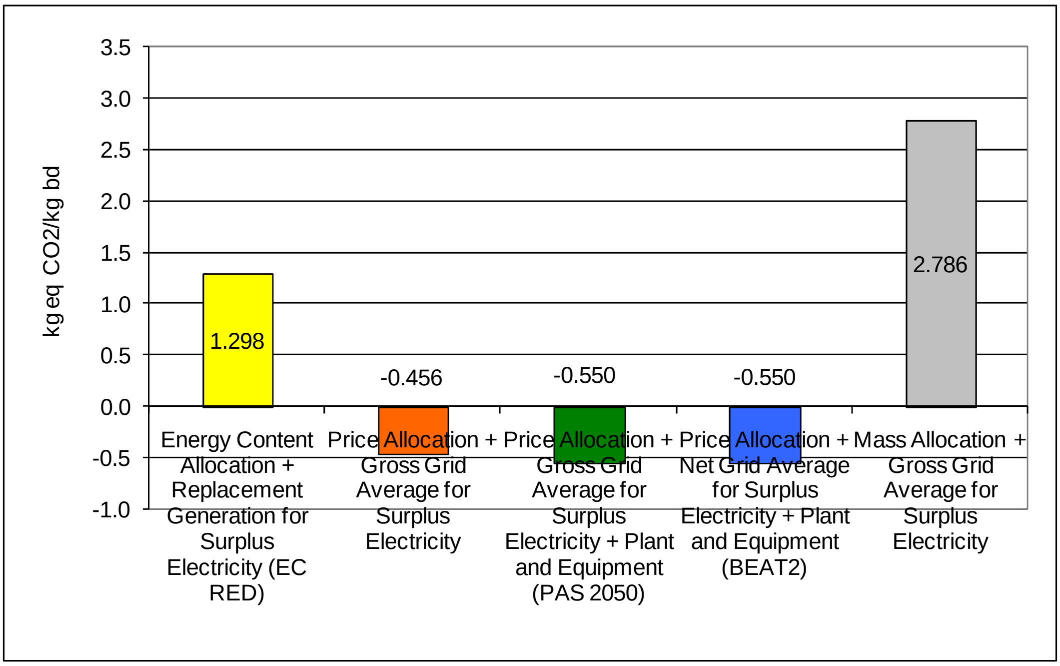



Figure 30 Effects of Calculation Methodologies for Jatropha: Biodiesel in Heat (only) Boiler Displacing Fuel Oil-fired Heat (only) Boiler



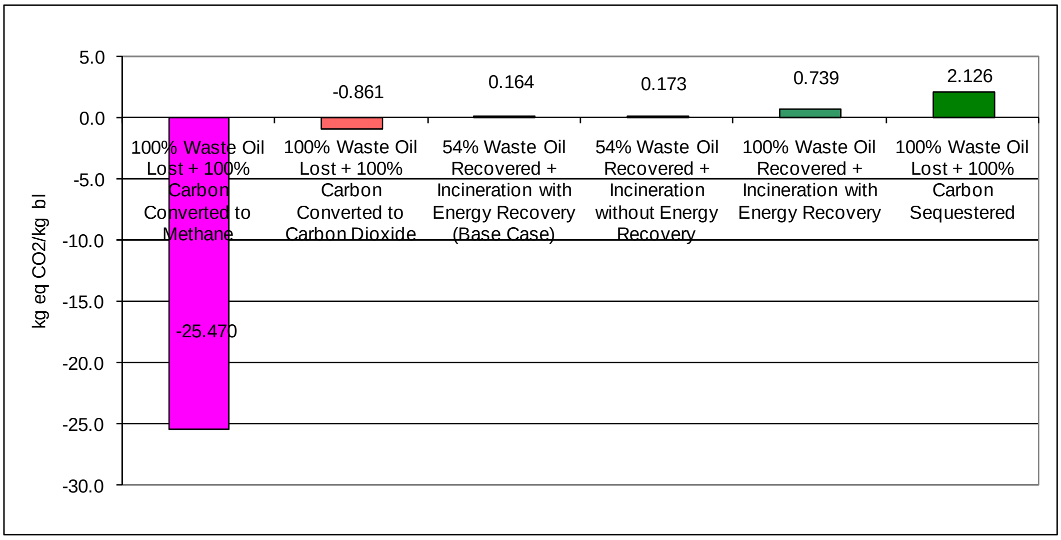
### 5.4 Biolubricant

Sensitivity analysis can also be applied to biolubricant and its displacement of motor oil derived from conventional crude oil. In the case of this particular end product and its current alternative, the most important sensitivities concern the assumed fates of oil lost during use and waste oil during disposal. The Base Case in the workbooks assumes that 54% of the biolubricant (and fossil fuel-derived motor oil) is recovered after use and that this is incinerated with energy recovery in the form of electricity generation. Carbon in the lost oil, which consists of the remaining 46% of the biolubricant (and fossil fuel-derived motor oil), is not taken into account.

The effect of changing these assumptions can be explored by means of the unit net GHG emissions savings for biolubricant derived from UK used cooking oil displacing conventional motor oil, as demonstrated in Figure 31. This particular biomass feedstock was chosen because it generates actual savings relative to conventional motor oil. If the waste biolubricant is incinerated without energy recovery, a slightly higher increase of 5% in savings can be achieved. However, if 100% of the biolubricant is recovered after use and incinerated with energy recovery, a larger increase of 351% in savings of the Base Case can be realised. The greatest savings arise when 100% of the biolubricant is actually lost during use and all the carbon contained (both biogenic and fossil) is sequestered. This amounts to a 1,196% increase in savings compared to the Base Case. Unfortunately, this large increase in savings is not sufficient to alter the net GHG emissions deficits (negative savings) of biolubricant derived from the other (cultivated) biomass feedstocks considered in this study.

In contrast, if 100% of the biolubricant is lost during use and all the carbon is converted into $CO_2$, any savings are reversed so that the biolubricant releases more total GHG emissions than conventional motor oil during production, use and disposal. The worst possible circumstance is when 100% of the biolubricant is lost during use and all the carbon contained is converted to $CH_4$. The actual outcome in terms of total GHG emissions benefits (or deficits) depends, crucially, on the specific fate of any lost biolubricant (and conventional motor oil). This sensitivity analysis demonstrates the need to improve knowledge on this particular issue to underpin any claimed GHG emission benefits for biolubricants derived from these sources of vegetable oil.

Figure 31 Sensitivities for Used Cooking Oil: Biolubricant Displacing Fossil Fuel-derived Motor Oil



### 5.5 Other Considerations

There are a number of other significant considerations which have not been examined in this study but which could be addressed using the relevant workbooks provided suitable data were available. One particular issue is the effect of cultivation practice mainly on total GHG emissions and, to a lesser degree, on primary energy inputs. It is possible to change input variables in the workbooks to explore the influence of different cultivation practices. However, in order to do this, it is necessary to access and apply consistent sets of data, rather than single data entries, to reflect an entire cultivation practice. The minimum consistent data set consists principally of the N fertiliser application rate (kg N/ha.a) and the crop yield or productivity (t/ha.a). Ideally, the diesel fuel consumption rate (MJ/ha.a) and the application rates of other fertilisers, ground conditioners and chemical treatments should be included in a complete data set. However, such information is not generally available for all the crops covered in this study. Instead, default values for cultivation data sets were mainly based on national statistics for long-established crops such as oilseed rape, soy beans and sunflowers. Typical commercial data were used for oil palms and jatropha. With this last crop which is relatively novel, the commercial nature of large-scale cultivation which has been represented in the relevant workbook may not reflect some expected benefits from growing this relatively novel crop on a small-scale, and/or on waste or degraded land, and/or without significant N fertiliser application rates and irrigation. However, if robust evidence emerges on such potential cultivation, subsequent data sets can be readily accommodated in the relevant workbook so that new representative results can be generated.

Other issues which have been excluded from this study are the effects of direct land use change (dLUC) and indirect land use change (iLUC). These can be very important considerations but the reliable estimation of their effects on total GHG emissions and subsequent savings depends on the availability of reliable information on related GHG emissions. Converting land from a previous use to oil crop cultivation, as encompassed by dLUC, relies on detailed information on net $CO_2$, $CH_4$ and $N_2O$ emissions. Available data were explored in the Gallagher Review in the UK (RFA, 2008) but it was apparent that such information could only be used with careful qualification. In particular, more detailed and extensive data are needed for a range of dLUC, soil types, climatic conditions, cultivation practices, etc., to provide reliable GHG emissions estimates. The displacement of land used for food crop cultivation to other parts of the world as a result of non-food crop production is incorporated in iLUC. The evaluation of subsequent net GHG emissions depends not only on robust land use conversion data but also on the precise mechanism by which land use is displaced. In particular, this requires the construction and operation of a global land use model which is a very challenging task. Both dLUC and iLUC are currently being addressed by relevant organisations such as the RFA in the UK and the European Commission's Directorate-General for Energy and Transport (DG-TREN). If and when suitable means for estimating the total GHG emissions impact of dLUC and iLUC become available, these can also be readily accommodated within the workbooks developed for this study.

# 6 CONCLUSIONS

From the results generated using the workbooks developed for this study, with Base Case default values and assumptions in compliance with the EC RED methodology, the following major conclusions can be put forward:

- Total GHG emissions savings can be achieved for the utilisation of used cooking oil in all end-use applications (heat and/or electricity, transport fuel and biolubricant) which displace all conventional fossil fuel-based alternatives considered in this study. This is because only transport is involved in the collecting used cooking oil with simple cleaning for refining for vegetable oil or en route to biodiesel.

- Total GHG emissions savings can be achieved with all the other (cultivated) biomass feedstocks considered in this study apart from:

    - Using refined vegetable oil from UK oilseed rape, US soy beans, Malaysian oil palms and Indian jatropha in electricity (only) generation to displace natural gas-fired electricity (only) generation.

    - Using refined vegetable oil from US soy beans and Indian jatropha in electricity (only) generation to displace UK grid electricity.

    - Using biodiesel from US soy beans and Indian jatropha in CHP generation to displace natural gas-fired CHP generation.

    - Using biodiesel from UK oilseed rape, US soy beans, French sunflowers, Malaysian oil palms and Indian jatropha in electricity (only) generation to displace natural gas-fired electricity (only) generation.

    - Using biodiesel from US soy beans and Indian jatropha in electricity (only) generation to displace fuel oil-fired electricity (only) generation.

    - Using biodiesel from UK oilseed rape, US soy beans and Indian jatropha in electricity (only) generation to displace UK grid electricity.

- Total GHG emissions savings can be maximised, in terms of the absolute amount of equivalent $CO_2$ saved, by using all the refined vegetable oils considered in this study in CHP generation to displace fuel oil-fired heat (only) production and UK grid electricity, or by using biodiesel in heat (only) production to displace fuel oil-fired heat (only) generation. In these instances, the displaced fossil fuel-based options have relatively high associated total GHG emissions.

- Total GHG emissions savings from using biodiesel, from all the sources considered here, in heat (only) production to displace fuel oil-fired heat (only) production are marginally higher than those savings from using biodiesel as a transport fuel to displace diesel derived from conventional crude oil. This is because of the relative total GHG emissions associated with fuel oil and diesel in their respective applications.

- However, total net GHG emissions savings from biodiesel used in transport are marginally higher than those for its use in heat (only) production displacing natural gas-fired heat (only) production, and in CHP units displacing natural gas-fired heat (only) production and grid electricity. Total net GHG emissions savings from transport biodiesel are significantly higher than those when biodiesel is used on CHP units which displace natural gas-fired CHP units.

- In general, of all the cultivated biomass feedstocks considered in this study, the highest total GHG emissions savings, in terms of the absolute amount of equivalent $CO_2$ saved, arises from the use of French sunflowers and Malaysian oil palms. This is largely due to the relatively low inputs into cultivating these biomass feedstocks.

- Whether main sensitivities could alter this relative pattern of total GHG emissions savings depends on specific considerations for each biomass feedstock:

    - Results for UK used cooking oil are relatively insensitive to road transport distances involved in collecting this biomass feedstock because road transport only comprises a comparatively small part of total GHG emissions.

    - Results for UK oilseed rape, French sunflowers and Malaysian oil palms are only slightly sensitive (negatively) to switching from the use of CHP units in processing to fossil fuel-fired heat (only) boilers and national grid electricity. This is partly due to assumptions concerning the sources of energy in the CHP units, their heat-to-power ratios and the implications of the way surplus electricity is treated in the EC RED methodology.

    - Results for US soy beans and Indian jatropha are moderately sensitive (negatively) to switching from the use of CHP units in processing to fossil fuel-fired heat (only) boilers and national grid electricity. This is mainly a consequence of higher heat and electricity requirements and the assumed sources of energy in the CHP units, their heat-to-power ratios and the implications of the way surplus electricity is treated in the EC RED methodology.

    - Results for US soy beans are most sensitive (negatively) to the use of irrigation in cultivation which can be a significant source of GHG emissions.

    - Results for Malaysian oil palms are most sensitive (positively) to the capture and flaring of $CH_4$ from POME which can be substantial component of total GHG emissions.

    - Results for Indian jatropha are moderately sensitive (positively) to avoiding the use of irrigation in crop cultivation which can be a reasonably important source of GHG emissions.

- In the specific cases considered here (refined vegetable oils used in CHP units displacing fuel oil-fired heating and grid electricity, and biodiesel used for heating displacing fuel oil-fired heating), application of allocation by mass in GHG emissions calculations results in the highest savings (the exception being refined oil from oilseed rape). The effect of applying different official methodologies for GHG emissions calculations affects each biomass feedstock differently in these specific cases:
  - Savings from UK used cooking oil are hardly affected by the choice of methodology because there is only one co-product (glycerine) that can be affected by allocation procedures and treatment of surplus electricity does not arise since it is assumed that CHP units are not used in processing.
  - Savings from UK oilseed rape are highest with the EC RED methodology, lowest (significantly lower) with the PAS 2050 and $BEAT_2$ methodologies, and intermediate with the RFA methodology. This is largely because of the effect of co-product allocation based on the high associated energy (energy content x mass) of rape meal relative to its low value (price x mass).
  - Savings from US soy beans are relatively similar with the EC RED, RFA, PAS 2050 and $BEAT_2$ methodologies. Any differences are mainly due to the effect of co-product allocation based on the high value (price x mass) of soy meal relative to its low associated energy (energy content x mass) as well as assumptions about substitution credits.
  - Savings from French sunflowers are highest with the EC RED methodology but similar to those with the RFA methodology and lowest (significantly lower) with the PAS 2050 and $BEAT_2$ methodologies. This is principally due to the relative balances of energy content, price and mass of co-products (sunflower meal, sunflower oil, and glycerine and biodiesel) and assumptions about substitution credits.
  - Savings from Malaysian oil palms are highest with the EC RED methodology but similar to those with the PAS 2050 and $BEAT_2$ methodologies. Any small differences are due to the relative balances of energy content, price and mass of co-products (press cake, palm stearin and palm oil, and glycerine and biodiesel).
  - Savings from Indian jatropha are highest with the EC RED methodology and lowest (very much lower or even reversed) with the PAS 2050 and $BEAT_2$ methodologies. This is principally due to the relative balances of energy content, price and mass of co-products (press cake, hulls, jatropha oil, and glycerine and biodiesel).
- The inclusion of plant and equipment in GHG emissions calculations (as part of the PAS 2050 and $BEAT_2$ methodologies) affects each biomass feedstock differently:

- Savings from UK used cooking oil are relatively unaffected because of the absence of cultivation and the relatively simple processing involved.

- Savings from UK oilseed rape, US soy beans and French sunflowers are significantly affected because of a combination of capital-intensive cultivation and processing.

- Savings from Malaysian oil palms and Indian jatropha are moderately affected because of less capital-intensive cultivation but relatively capital-intensive processing.

- Total primary energy savings, as a measure of avoided energy resource depletion, are demonstrated for all biomass feedstocks and end-use applications (heat and/or electricity, transport fuel and biolubricant) apart from:

  - Using biodiesel from US soy beans and Indian jatropha in electricity (only) generation to displace natural gas-fired electricity (only) generation.

- Amongst all the biomass feedstocks considered in this study, only biolubricants derived from UK used cooking oil are capable to reducing total GHG emissions relative to motor oil derived from conventional crude oil, although this depends, critically, on the fate to losses during use and the chosen waste disposal method:

  - Highest savings are achieved if 100% of the biolubricant is lost and all contained carbon is sequestered.

  - Next highest savings are achieved if 100% of the biolubricant is recovered and incinerated with energy recovery in the form of electricity generation (which displaces UK grid electricity).

  - Savings are noticeably reversed, resulting in higher total GHG emissions than motor oil derived from conventional crude oil if all the biolubricant is lost during use and contained carbon is eventually converted to $CO_2$ or, in the very considerably worst case, $CH_4$.

  - It is not possible to specify the actual fate of carbon contained in lost biolubricant (and lost motor oil derived from conventional crude oil) due to a lack of robust scientific evidence.

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