ABSTRACT

Life-cycle assessments (LCA) of biodistillate fuels are becoming increasingly important for policy decisions regarding alternative fuels. However, due to the data-intensive and assumptive nature of LCAs, rarely do two different studies produce comparable results. To add to the complexity, effects of indirect land use changes are now being incorporated into LCA models. This development is influencing policy decisions and generating much controversy.

A literature survey of 55 different LCA studies of biodistillate fuels was conducted. The comparison of energy requirements and global warming potential (GWP) impacts of these studies help to illustrate which data inputs and assumptions most strongly affect the results, and wherein the major discrepancies lie.

Life-cycle energy results are typically reported as energy return (ER), meaning the heating value of the biofuel divided by the total fossil energy inputs to produce the fuels. Most studies report significantly higher ER values for biodistillates (both biodiesel and renewable diesel) compared to conventional diesel fuel. Similarly, most LCA studies show significant GWP reductions for biodistillates compared to conventional diesel. However, due to lack of consistency in LCA approaches and assumptions, considerable uncertainty still exists regarding the accuracy of most LCA results.

INTRODUCTION

Global climate change and concerns about greenhouse gases, dwindling supplies of fossil fuels and national energy security are driving growth in production and use of biofuels. In the US and EU, alternative fuels use is becoming increasingly regulated through policy and mandates. A goal of these policies is to decrease greenhouse gas (GHG) emissions relative to fossil fuels. To ensure this is achieved, LCA models are being incorporated. For example, California recently adopted its Low Carbon Fuel Standard (LCFS) regulations to reduce the carbon intensity of transportation fuel used in California by 10% by 2020. The regulation is being supported by the GREET LCA model that has been modified for California (CaGREET model) to ensure that full cradle-to-grave production and use of the fuel will comply with reduced CO₂ emission requirements.

While data documentation and format are standardized by ISO, LCA methodology is often convoluted, and results are heavily dependent on data inputs and on numerous assumptions. To further complicate the matter, the effects of indirect land use change (iLUC) are becoming of increasing concern. In fact, results from the CaGREET model are paired with LUC results from the GTAP (Global Trade Analysis Project) economic model for LCFS regulations. Recently, LCA models are being termed as “attributional” or “consequential” depending on the inclusion of indirect effects.
As part of a study sponsored by the Coordinating Research Council (CRC) to assess the state-of-knowledge regarding plant- and animal-derived biofuels as blending materials for ultra-low sulfur diesel (ULSD) fuel in transportation applications, a literature survey of LCA studies on biodistillate fuels was completed. The survey excluded LCA studies strictly related to diesel. 55 studies related to the production of biodistillate fuels from a variety of feedstocks via different processing methods. This paper discusses critical disparities in methodologies and assumptions of LCA that result in significant differences in both GWP and energy use predictions.

**FUEL LCA OVERVIEW**

LCAs provide a tool to evaluate the “cradle-to-grave” environmental impacts that result from all stages of a product’s life, from manufacturing through disposal. These environmental impacts can include energy use, emissions produced, water consumption, eutrophication and acidification potential among other factors. According to a recent EPA report, there are three steps involved in conducting an LCA to assess these energy and environmental impacts:

1. Compiling an inventory of relevant inputs and outputs of a process stream
2. Evaluating the potential impacts associated with the inputs and outputs
3. Interpreting the results to make informed decisions

The inventory for a full-fuel LCA includes all energy flows and emissions associated with the fuel production and use—starting with the raw material and ending with fuel consumption. For a biofuel, this includes all inputs and requirements for feedstock growth, harvesting, fuel production, distribution and combustion as well as intermediate transportation steps. These steps are broken into two parts: well-to-tank (WTT) and tank-to-wheels (TTW). The combination of the two parts represents the complete well-to-wheels (WTW), or cradle-to-grave, life-cycle for a transportation fuel.

The WTT pathway for a bio-distillate fuel commonly includes growth of the crop which may involve LUC and farming inputs such as fertilizers, harvesting of the crop, processing or crushing to extract the oil, fuel production (via transesterification or some other method), and distribution to the fueling station. This also includes any intermediate transportation steps. Increasingly, WTT pathways may also incorporate ILUC effects, in which the changes in crop use may result in new crops being planted elsewhere on a global scale. Accounting for this requires linking of LCA models to economic models.

The TTW analysis includes combustion of the fuel in a vehicle, and depends on the type of vehicle, its efficiencies and driving scenarios. Common LCA practice for biofuels is to include only fossil carbon inputs. Thus, non-fossil carbon emitted during combustion of a biofuel is ignored (or offset by carbon uptake during plant growth) in the TTW portion of the life-cycle. (This is sometimes referred to as the “carbon neutral principal,” since the carbon being emitted is the same carbon that was recently absorbed by the plant during its growth through photosynthesis. Therefore, there is minimal net contribution to GHG emissions from combustion of biofuels, though NOx and other minor pollutants do contribute to a small degree. This principle of carbon neutrality is recognizable flawed and is being reviewed, especially as land use changes become more influential in the overall environmental impacts. Because the TTW portion of most biofuels’ life cycle is so small, the WTT results for GHG emissions are generally similar to the complete WTW results.

Another important issue in LCA is allocation of environmental burdens among the biofuel and multiple co-products generated in the fuel life cycle. This issue can become very complicated, especially if the co-products are applied in different industrial sectors. For example, the processing of biomass feedstock could generate co-products that are used as food, feed, nutrient supplements, chemicals, and even clothing materials (i.e., leather). Methods for estimating co-product allocation fractions often vary among the biofuel pathways due to the unique nature of each pathway. Impacts of co-product allocation are especially significant if the quantities of the co-products are large (e.g., soybean meal in the LCA of soybean oil-based biodiesel).

Life-cycles of biofuels are also very data-intensive, requiring specific inputs for each step of the process, including fertilizer use, harvest yield, electricity mix, processing efficiencies, and many other factors. Clearly defined boundaries are crucial for calculating robust LCA results. Data used are often specific for a particular feedstock or process, although some databases use averages for a larger region. Because of variations in pathway boundaries and assumptions among studies, the results require careful interpretation. LCA results are best used for comparison of energy use and emissions relative to conventional petroleum fuels within the study itself, and not for direct comparisons among different studies.

**LCA MODELING TOOLS**

To date, a variety of LCA modeling tools and databases have been developed, many of which are available in the public domain. However, only a handful of models are free to users; the GREET model maintained by Argonne National Laboratory (ANL) and the LCI database by the National Renewable Energy Laboratory (NREL) are currently free to the public. These LCA models vary significantly in their structure as well as in the type and number of pathways included. For example, some models (the BESS model) are specific for only one type of fuel pathway, while others (GREET, LEM, LBST, and
SimaPro models) deal with multiple pathways. Several private companies have also developed their own LCA models. (S&T)2 Consultants recently performed a review of 37 LCA tools. Of those, the 11 listed in Table 1 are applicable for biofuels, although biodistillate pathways are quite limited (or missing completely) in some cases.

Table 1: LCA Tools for Transportation Fuels. (Taken from References(17,22))

<table>
<thead>
<tr>
<th>Model</th>
<th>Biodiesel Pathways</th>
<th>Region</th>
<th>Publicly Available</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>BEES</td>
<td>None</td>
<td>US and EU data</td>
<td>Yes</td>
<td>Adapted for bio-based products</td>
</tr>
<tr>
<td>BESS</td>
<td>None</td>
<td>US</td>
<td>Yes</td>
<td>Specific for corn-to-ethanol</td>
</tr>
<tr>
<td>EBAMM</td>
<td>None</td>
<td>US data</td>
<td>Yes</td>
<td>Excel model uses data from 9 studies and outcomes from each dataset</td>
</tr>
<tr>
<td>EIO-LCA</td>
<td>None</td>
<td>US and EU data</td>
<td>Yes</td>
<td>Can model ethanol</td>
</tr>
<tr>
<td>GaBi</td>
<td>None</td>
<td>EU Germany</td>
<td>Yes - $$</td>
<td></td>
</tr>
<tr>
<td>GEMIS</td>
<td>forest residue</td>
<td>EU data</td>
<td>Yes</td>
<td>Limited pathways.</td>
</tr>
<tr>
<td></td>
<td>palm, tallow,</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>yellow grease and</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>marine oils.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GREET</td>
<td>Soybeans</td>
<td>US data</td>
<td>Yes</td>
<td>100 pathways, used in US policy</td>
</tr>
<tr>
<td>LBST E3</td>
<td>Soybeans and</td>
<td>EU data</td>
<td>No</td>
<td>Petroleum and bio-based fuel pathways, used by European Commission’s</td>
</tr>
<tr>
<td>Database</td>
<td>rapeseed</td>
<td></td>
<td></td>
<td>Joint Research Centre</td>
</tr>
<tr>
<td>LEM</td>
<td>Soybeans</td>
<td>US data</td>
<td>No</td>
<td>Basis of GHGenius.</td>
</tr>
<tr>
<td>SimaPro</td>
<td>None</td>
<td>EU and US data</td>
<td>Yes - $$</td>
<td>Has biodiesel processes, but no pathways.</td>
</tr>
</tbody>
</table>

Use of LCA models as support tools for carbon-based regulations requires that they be transparent, comprehensive, reliable, and flexible for integration of new pathways. Problems with existing models include lack of documentation, non-transparent methodology, built-in algorithms, lack of updated process information, and over-simplified assumptions for certain pathways. All these issues add uncertainty to the results of LCA models, and demonstrate the nature of LCA as an evolving science. At present, no model is accepted nationally or internationally as the “gold standard.”

Currently, U.S. EPA uses the GREET model to provide estimates of GHG reduction thresholds for the four categories of biofuels defined in the Energy Independence and Security Act (EISA 2007).(1) The California Air Resource Board (CARB) employs the CaGREET model, a modified GREET model with California-specific inputs, in its LCFS regulations. Similarly, GHGenius is used for Canadian policy.

A key to address inconsistencies in these LCA models and LCA-based regulations is development of a standardized methodology and a robust and reliable model. This will require a coherent and continuous effort with involvement of different industries and disciplines in the scientific community.

VARIATIONS IN MODELING

While established databases and modeling tools exist, differences in LCA approaches are still common. Two models can be run with the same types of assumptions and produce very different results.(23) Standards have been implemented to maintain consistency in data (ISO 14044:2006 provides modeling requirements and guidelines, and ISO 14048:2002 outlines standards for data documentation and format within the model(7,8)), but they do not specify methodologies to be used. Because results of different assessments can vary greatly, fuel LCA models are typically used to determine relative benefits of different scenarios in which conventional petroleum fuels are displaced with alternative fuels.

Differences in methodologies arise from variations in defining fuel pathways, scenario boundaries, input assumptions, and dealing with co-products. Most LCA data inputs are specific to the process, fuel type, or region that is being evaluated. For example, crop yields and fertilizer use can vary dramatically based upon type of crop or growing location; also, energy use for an advanced production process may not be well established and must be estimated from scant data. Generally, LCA inputs and assumptions represent reported industry-wide averages.(24,21,25) However, some data may come from literature rather than process measurements, especially in cases of new technology.

The quality of input data clearly affects LCA results for biofuels. As defined by Wang,(26) some of the key issues include the following:

- land use changes
- nitrogen fertilizer for plant growth
- conversion factor of nitrogen fertilizer to N2O
- crop yields
- other farming energy and chemical requirements
- energy use in biofuel processing plants, including the type and amount of process fuel
- credits given to co-products
- scale of production

Land-Use Change

Growth of the biofuel industry is likely to result in increased demand for crops, which in turn could lead to
modifications of existing agricultural lands, development of marginal lands, or creation of new agricultural regions. These land use changes (LUC) may result in the release of soil carbon. This topic of LUC and the way that it is considered (or not considered) in LCA modeling has drawn considerable attention, partly due to recent publications by Searchinger et al.\(^\text{(27)}\) Fargione et al.\(^\text{(28)}\) and Crutzen et al.\(^\text{(29)}\) Both direct and indirect LUC (iLUC) may have significant impacts on the overall life-cycle of a fuel. Direct impacts are those that are associated directly with the cultivation of feedstocks used to produce a biofuel in the region where it is used. This includes modification to soil carbon and variations in above ground biomass from preparation of existing crop-lands (including fertilization during cultivation) or conversion to new crop-land.\(^\text{(17)}\) Indirect effects are those that could potentially arise when a crop is newly produced in one region of the world in response to changes in supply or demand in another region.

Most LCA models include some type of direct LUC assessment to address changes in GHG emissions resulting from modifications to soil carbon. LCA models which only include direct effects have been defined recently as attributional LCA (ALCA)\(^\text{(9,10)}\) ALCA includes only those impacts derived from production and consumption processes. Even methods of including direct LUC are somewhat controversial, specifically with respect to biologically-produced \(\text{N}_2\text{O}\) emissions.\(^\text{(28)}\) The IPCC consensus is that \(\text{N}_2\text{O}\) has a GWP 296 times that of \(\text{CO}_2\), so small changes in \(\text{N}_2\text{O}\) can result in significant differences in GWP.\(^\text{(30)}\) Therefore, it is crucial to account for all \(\text{N}\) inputs and outputs from cultivation of land to grow biomass -- including crop residues, fertilizer, \(\text{N}\) fixation, manure, deposition, gaseous losses, crop output, runoff, \(\text{N}\) transfer between co-rotated crops, and others. It is also important to know how these factors change over time.\(^\text{(31)}\) Variations in assumptions about \(\text{N}_2\text{O}\) can swing the final GWP results of a particular biofuel scenario from positive to negative, compared to a conventional baseline fuel.

The IPCC recommends use of an \(\text{N}_2\text{O}\) conversion factor for LCA modeling to estimate the amount of \(\text{N}_2\text{O}\) emitted per gram of Nitrogen fertilizer input. This factor has a significant impact on the overall GHG emissions during the agricultural stage of a biodistillate’s life-cycle, but its value is very controversial. Many models use a value in the range of the IPCC-recommended factor of 1.325%. The GREET model uses the IPCC value\(^\text{(26)}\) and the GHGenius model uses a factor of 1.125%.\(^\text{(17)}\) Using these relatively low conversion factors generally results in GWP benefits for biodiesel pathways relative to conventional diesel. However, Crutzen et al.\(^\text{(29)}\) concluded that the IPCC emission factor for \(\text{N}_2\text{O}\) was seriously underestimated, and recommended a conversion value equivalent to an IPCC factor of 2.24-3.74.\(^\text{(26)}\) This change results in biodiesel pathways having increased GWP relative to conventional diesel. Delucchi’s LEM model, which includes a more comprehensive nitrogen balance than other models, predicts a 50% increase in life-cycle GHG emissions for biodiesel relative to petroleum diesel, largely because of \(\text{N}_2\text{O}\) impacts.\(^\text{(32,31,33)}\)

How indirect effects are included in LCA is even more controversial, and has been a topic of recent publicity and concern as having potentially serious adverse GHG impacts. Searchinger’s paper discusses the possibility that as crops are diverted to produce more fuels in one geographic location, increased crop production will be required elsewhere to compensate. This increased production could occur through displacement of existing crops, expansion of croplands, or intensification of existing production -- though economic equilibrium only occurs for expansion or intensification.\(^\text{(23)}\) Expansion of croplands may require reducing forest lands or other fallow lands elsewhere, which could result in extremely large releases of \(\text{CO}_2\) previously sequestered by roots and soil. Intensification of production may require more fertilizer usage. Both could have a net-negative GHG effect on the biofuel’s life-cycle.

Many LCA models do not include iLUC effects because they are much more difficult to analyze and require subjective assumptions which contain substantial uncertainty. However, policy is trending toward including iLUC into already required LCA models.\(^\text{(34)}\) To do this, an economic model is required to estimate the global economic responses to supply and demand changes. For example, CARB is working to link its CaGREET model with the GTAP economic model in an effort to include the effects of iLUC.\(^\text{(35)}\) Other models being utilized include FASOM (Forest and Agricultural Sector Optimization Model from Texas A&M University), and FAPRI (Food and Agricultural Policy Research Institute at Iowa State University).\(^\text{(34)}\)

LCA models that include indirect effects have been defined recently as “consequential” LCA (CLCA).\(^\text{(10)}\) CLCA models generally are linked to economic models to generate feedback loops that reflect how changes in supply and demand affect price elasticities and co-product markets. However, these models produce high levels of uncertainty in the results, including concerns about overlapping boundaries and double-counting of emissions.

**Methods of Dealing with Co-products**

Several by-products are produced during the manufacturing of biodiesel; for example, animal feed meal is produced during the oil extraction process, and glycerin is produced during transesterification. Other co-products such as naphtha or propane may be produced in renewable diesel manufacturing involving catalytic hydroprocessing.\(^\text{(36)}\) Common practice in LCA modeling is to allocate some of the energy and emissions produced during the fuel life-cycle to these co-products since they can replace other similar products in the market. The following methods of allocation are commonly used.\(^\text{(37,38,39)}\)
Physical Allocation—Environmental impacts are allocated to the biofuel and each by-product based upon a common physical parameter such as mass (kg) or energy (MJ). A drawback of this method is that it does not consider the actual environmental impacts that have been offset by replacing other products. The physical allocation method simply assumes that all forms of mass or energy are of equal value.

Economic Allocation—The market price of the biofuel and any by-products drive the allocation of energy and emissions. This method has similar drawbacks to the physical allocation method in that it does not consider actual changes to environmental impacts.

Expanded Allocation (Displacement or Substitution Method)—By-products are assumed to replace existing products. The environmental impacts from the replaced products are subtracted from the emissions and energy needed to produce the biofuel. This requires that the environmental impacts of the replaced product be known. Additionally, the expanded allocation method does not make corrections for changes in scale.

No Co-Product Allocation—All energy and emissions incurred in the lifecycle are attributed to the final biofuel product. While perhaps the easiest approach to use, failing to allocate any energy or environmental impacts to co-products is clearly an over-simplification of reality.

The choice of allocation method may significantly affect the final results of the LCA. Several studies in the literature have examined the effects that different allocation methods have on the results. Bernessson, et al. studied the effects of all four allocation methods listed above, as well as a range of production plant sizes. \(^{(37)}\)

They found that differences in plant size were almost negligible in some cases, but the allocation method had significant impacts, reducing GWP by a factor of 2 to 3 compared to no allocation. Guinee and Heijungs found that different allocation methods could result in up to a 250-fold difference in GWP in extreme cases. \(^{(39)}\)

Physical and economic allocation methods are generally considered part of ALCA methods, while the expansion method is considered a CLCA model approach, since it requires specific knowledge about the market effects. \(^{(10)}\)

Changes in scale are generally neglected in ALCA, but may or may not be included in CLCA. For example, many studies give glycerin a by-product credit; however, in some regions, the glycerin market may already be saturated from the soap making industry. If this market is already saturated, it would not be able to accommodate extra glycerin. Thus, to legitimately allocate energy or emissions to this by-product, another market (such as fuel combustion) must be identified.

**BIODIESEL LCA LITERATURE REVIEW AND RESULTS**

A literature review of LCA studies of biodiesel pathways was conducted. The review considered 55 published papers and reports covering a broad range of feedstocks and methods of production. Some studies compared biodiesel to conventional diesel while others considered only a single fuel, but investigated differences in assumptions, processes, or life-cycle scenarios. The most common feedstocks were rapeseed (in many EU studies) and soybeans (in many U.S. studies). Most studies considered biodiesel production via transesterification with methanol, though a few also investigated renewable diesel produced via catalytic hydroprocessing. Each paper is identified by number and briefly summarized in the Appendix.

To compare differences in results among these published studies, the environmental impacts are shown both on an absolute basis and relative to the reference fuel used. Both the energy and GHG emissions are discussed further.

**ENERGY**

The life-cycle energy inputs required to produce and deliver a unit of fuel is one of the impacts most frequently assessed in an LCA. This is determined by summing the net energy inputs throughout the life-cycle process, and subtracting any energy credits (such as those from co-product allocation). Common practice in biofuel LCA is to include only fossil energy inputs, but not renewable inputs such as the energy content of the plant itself. In contrast, the energy requirements to make conventional diesel are almost entirely fossil energy (including the energy content of the petroleum itself).

The net energy required to produce each unit of fuel is then used to assess the overall energy benefit or energy return (ER) of the entire process. The ER is determined by dividing the energy out of the process (the heating value of the fuel) by the total life-cycle energy inputs. A net energy benefit results when the ER is greater than one; an ER less than one indicates more energy is required to produce the fuel than is contained in the final product. [This value of ER is sometimes called Energy Return on Investment (EROI).] The ER value provides a normalized means to compare biofuel energy requirements to conventional fuels. Excluding the renewable energy requirements to produce bio-distillates typically results in a favorable ER compared to conventional diesel, which has an ER less than one as a result of the large fossil energy requirements.

In addition to total ER, some studies explored the nature of the energy sources used in the biofuels' life-cycle, particularly the use of petroleum. For certain policy purposes, it may be desirable to reduce petroleum use, even though this could result in greater use of coal (or other fossil fuels) and lower overall ER. These policy
issues regarding petroleum reduction are not addressed in this review.

Of the 55 studies examined, 32 reported an ER value—or something equivalent. Fig. 1 shows the ranges of ER results from each. A single point indicates a study in which only one result was reported; vertical bars represent the range of values reported. In some cases, the range represents the high and low values for a single scenario; in other cases it encompasses values for numerous scenarios with a single feedstock. The numbering refers to the study numbers provided in the Appendix, which provides a more detailed summary of results from each study.

Note that the x-axis in Fig. 1 (and subsequent figures) is a time line, representing the year in which the study was published. Also note the break in the x-axis after the first study in 1998 to indicate a gap in time, and the break after 2006 to indicate a slight change in scale. The figure illustrates the increase in number of LCA publications related to biodistillates in recent years. Additional spacing along the x-axis was used to avoid overlapping results from each study.

Several studies compared biodiesel ER to a reference fuel (typically conventional diesel), which is shown in Fig. 1 as dark gray circles. (In a few cases, the reference fuel was some other alternative fuel such as ethanol, which is not shown here). In nearly every case, the life-cycle ER for petroleum diesel was below one, and the life-cycle ER for biodistillate fuels was above one.

Figure 1 clearly illustrates the variability in results among different studies, whether for traditional methods of production (biodiesel via transesterification) or 2nd Generation methods (renewable diesel via hydroprocessing). Although the results are quite diverse, generally a net energy benefit (ER>1) for biodiesel is shown. The mean value reported is 3.1, with most cases falling below an ER value of 4. Of the studies reporting ER values >4, many are for renewable diesel (Study Nos. 28(36), 45(40), 50(41) and 51(42)). The ER values when tallow is used as the feedstock tend to be slightly higher, depending on the boundaries of the process (Study Nos. 17(43), 45(36), 50(41) and 51(42)). Studies regarding jatropha (Study No. 32(44) and No. 48(45)) report fairly high ER values as well. Among the biodiesel cases reporting high ER values, Study No. 10 shows a broad range of ER values due to a variety of calculation approaches. Study No. 26 reported high and low values for transesterification of rapeseed based on allocation of co-products or no allocation for specific use on an organic farm.1(46) The assumptions used in this paper are specific to the farm and its proximity to a production plant, which results in the higher estimates.

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Many of the studies were completed for EU scenarios, and make comparisons between rapeseed and sunflower oil feedstocks. However, even these results are not consistent. Studies numbered 6, 20, 22, and 42 (Venturi,

Cocco,

Edwards,

and Prieur,

respectively) all compared rapeseed and sunflower within specific regions in the EU. Study Nos. 6 and 20 were both within Italy. No. 42 was for French conditions, and No. 22 was a broad study for average EU 25 conditions. Although the three studies for specific countries showed rapeseed to have a slight advantage over sunflower, Study No. 22 for average EU conditions showed the opposite. Similar inconsistencies are reported throughout the literature. Several critical studies will be discussed in more detail to help identify the reasons for these differences.

Critical LCA Studies for Energy

Some of the 55 LCA studies were identified as critical based on the frequency of citation in other studies, the quality of the assumptions, the number of scenarios studied, and the robustness of the results. A brief description of the energy results for each of these critical studies is given below.

Study No. 1 was published by NREL in 1998. This frequently cited study is considered one of the most authoritative references for biodiesel LCAs in the U.S. It compared the environmental impacts of biodiesel with those of petroleum diesel, and included a comprehensive assessment of each, as well as a detailed sensitivity analysis of the inputs. The ER range shown in Fig. 1 represents a single high and single low value, where the high value (3.2) includes only the fossil energy inputs to produce biodiesel, and the low value includes all energy inputs. A net energy benefit results when considering only the fossil energy inputs. The fossil ER of 3.2 is frequently cited and is used as a reference value for comparison in numerous studies. The ER calculated for petroleum production was less than 1, resulting in nearly a four-fold energy benefit for biodiesel compared to petroleum diesel. This study also included a detailed emissions analysis (for CO₂) and comparison between petroleum and biodiesel use in an urban bus. (The LCA results for CO₂ emissions will be discussed in the next section.)

Study No. 6 (Venturi) compared biodiesel production from rapeseed, soybeans and sunflower seed in Italy, using a range of crop yields, based on differing regional productivity. This study also compared co-product allocation by energy content with no co-product allocation. The ER was below one for each feedstock when the no co-product allocation method was used. With co-product allocation, both sunflower and soybean still resulted in an energy dis-benefit for low crop yields. Rapeseed provided the only favorable energy return for all crop yield ranges when some of the energy use was allocated to the co-products.

Study No. 8 (Bernesson) investigated how changing the allocation of co-products affects both energy and global warming impacts of biodiesel. (This study was conducted by a group at the Swedish University of Agricultural Sciences, who also published Study No’s. 26 and 34, which were not identified as critical studies due to the narrower scope of each.) Use of different co-product allocation methods dramatically affected the final LCA results. All four allocation methods discussed above were applied to small, medium and large-scale production facilities. Results showed that the size of the plant had little impact on the overall ER, but the allocation method had significant effects. Assuming no allocation to by-products resulted in low ER values. Higher values resulted from all four allocation methods. Not shown in Fig. 1 is the ER for the expanded allocation method, which allows compensation for energy requirements of displaced products. When the expanded allocation method was applied, the energy subtracted from the co-product allocation was greater than the energy inputs to the system, resulting in a negative energy balance, indicating that the process is a net supplier of energy.

Study No. 10 (Janulis) investigated transesterification of rapeseed oil in Lithuania. Although the scope was very specific, this is identified as a critical study due to the broad range of impacts quantified and the frequent citation of the paper throughout the LCA literature. In total, over 20 scenarios were investigated and three different methods of calculating ER were used. The scenarios included different agricultural practices, transesterification with methanol compared to ethanol, and cold pressing oil extraction versus higher yield hot pressing technology. The results in Fig. 1 represent all three ER methods that were calculated: the bar at 3.2 is the upper value for ER using the traditional calculation (LHV of fuel/life-cycle energy inputs). The other two ER calculation methods included different approaches of assessing co-product energy: one comparing the energy accumulated in all products with total energy consumed; the other (called the ecobalance) comparing the energy in the fuel with the energy related solely to biofuel production. This study provides a comprehensive assessment of how changes in technology can help improve the overall energy balance of biodiesel. The results also show that ethyl esters have slightly higher energy efficiency than methyl esters, and that advancement in agricultural technology can help to further improve the ER value of biodiesel.

Study No. 13 (Gartner et al.) investigated 2nd generation biodiesel production of NExBTL™. NExBTL is produced commercially via a catalytic hydroprocessing technology by Neste Oil. The evaluation is based on data collected from Neste Oil’s commercial facility located in Poorvoo, Finland. The study also included analysis for average EU conditions. The main differences between locations are the energy mix and use of natural gas. Both energy and GHG benefits were
investigated for renewable diesel production using rapeseed oil or palm oil from a variety of origins (Europe or Malaysia). The ER values were reported per ton of NExBTL produced, where the energy content of NExBTL is 44GJ/t. Results for rapeseed showed ER to range from 2.2 to 2.8, depending mainly upon where the rapeseed was grown. The energy savings for producing NExBTL was found to be over 60% relative to petroleum diesel. Other studies related to NExBTL production are Study No. 31 (which is not included in the ER Figure 1) and study No. 53, which supports CARB’s LCFS and will be discussed later in more detail.

Study No. 22 (Edwards et al.) was a complete WTW investigation conducted by the Institute for the Environment and Sustainability in the EU, along with EUCAR and CONCAWE, to aid EU policy decisions regarding alternative fuels. This study included detailed descriptions of a large array of alternative fuel pathways, with comprehensive appendices for WTT, TTW and WTW results for each fuel type. Results for biodiesel and a petroleum diesel reference fuel are included, along with synthetic diesel and DME produced from biomass sources such as waste wood and farmed wood. The focus of the study was on policy in the EU, so EU feedstocks of rapeseed and sunflower were investigated. The expanded allocation method was applied in all cases, with glycerin use as either an animal feed or a chemical feedstock.

Study No. 44 (S&T2 Consultants) was considered a critical study due to its level of detail. Two separate analyses were performed: one to compare results of the GHGenius model to the GREET model (depicted by the first range of values in Fig. 1) and one to compare GHG and ER results for biodiesel production from different feedstocks using the GHGenius model (depicted by the two individual points for canola and soybean.) This study also provided detailed assumptions, and included sensitivity analyses.

Study No. 17 presented ER results for the production, processing, and conversion of beef tallow to biodiesel. Total energy use in the LCA included direct energy inputs in the processes, and the energy embodied in raw material manufacture, i.e. fertilizer synthesis. Several scenario analyses were performed, where the effects of system boundaries and co-product allocation methods were compared. Both factors had significant impacts on the LCA results. For example, when tallow was treated as a waste material (no upstream carbon intensity included in the LCA), energy ratios ranged from 5.9 to 17, depending on the allocation methods. If rendering was included in the LCA, the ER results were between 3.5 and 5.7.

Kalnes et al. published two studies for UOP’s Ecofining™ Process: Study No. 28 and Study No. 45. Study No. 45 investigated three different feedstocks for the Ecofining™ process (rapeseed, palm oil, and tallow), and investigated how using biogas affected the energy and GHG emissions. Study No. 28 investigated both soy and palm oil. Both studies compared renewable diesel to biodiesel, and to low-sulfur petroleum diesel. The renewable diesel ER ranges for each feedstock are shown in Fig. 1, as well as the biodiesel and petroleum diesel reference results. The differences between the two studies are quite significant: Study No. 28 reports nearly double the ER for renewable diesel from palm oil than Study No. 45. The most notable difference between the studies is that N2O emissions were neglected in Study No. 28, but included in Study No. 45 -- although this should affect GWP results more than the ER results. (Not enough detail is given in either publication to discern if this is the only difference between the studies.) In both studies, renewable diesel resulted in a higher ER value compared to biodiesel and to conventional diesel. In Study No. 45, use of biogas to generate process power was also investigated, providing the range of results shown for palm oil in Fig. 1. Using tallow as a feedstock gave an ER of 9.1 for renewable diesel. This very large benefit resulted from the assumption that tallow was a waste product, and its only energy inputs came from transportation to the processing facility and from production of the renewable diesel itself. Other studies investigating the Ecofining process include Studies No. 46 and 54.

Study No. 46 (Argonne National Laboratory) reflects the biodiesel pathway results from the GREET model. The only biodiesel feedstock currently included in GREET is soy oil. The model calculates both GWP and ER for traditional biodiesel from transesterification and for two different types of renewable diesel: (1) using UOP/Eni Ecofining™ process, and (2) using Canada’s SuperCetane™ process. The results from a total of twelve biodiesel scenarios were included, based on three types of processes and four different allocation methods. The allocation methods investigated include displacement (or expanded allocation), allocation by both energy and market value, and a hybrid case involving both displacement and allocation. This hybrid approach provided the upper ER estimate for biodiesel. Of the two renewable diesel cases investigated, the method for SuperCetane™ generated more co-products (soymeal, fuel gas and heavy oil) per unit of product than did the Ecofining process. Therefore, the results for SuperCetane™ were more strongly affected by the co-product allocation method selected. Additionally, the fuel gas generated in the production of SuperCetane™ was used to power the process, which added extra energy value. Although cultivation and fertilization inputs were investigated in the GREET model, no indirect LUC was included in this investigation.

Study No. 50 also investigated the LCA of tallow-derived renewable diesel using a co-processing hydrotreating technology developed by ConocoPhillips. The system boundary included the production of animal feed, animal production in the feedlot, meat processing and rendering, and tallow conversion to renewable diesel. Sensitivity analyses were performed for several
assumptions such as transportation mode and distance, feed to animal weight gain ratio, and \(\text{N}_2\text{O}\) emission rate. Effects of allocation method were also compared. ER values varied from 4.5 to 7.1 under different scenarios. The WTW GHG emissions for tallow renewable diesel were 80-88% lower than petroleum diesel.

Study Nos. 52 and 53\(^{(54,52)}\) are LCAs published by CARB in support of the LCFS. Study No. 52 considered biodiesel from Midwest soy-oil, while No. 53 considered renewable diesel produced via hydropyrolysis related to Neste-Oil’s NExBTL. Since CARB links CaGREET to the GTAP model to estimate indirect effects, Study No. 52 is one of the few studies to include a specific number for GWP related to indirect effects. Both studies, include fossil energy alone as well as total energy. The ER values based on fossil energy only are shown by the single points in Fig. 1, whereas the bar reflects the values including total energy. When considering only fossil energy requirements, either production method resulted in a favorable energy benefit relative to petroleum diesel.

More details on the remaining studies included in Fig. 1 can be found in the Appendix.

GREENHOUSE GAS EMISSIONS

Frequently in LCA studies of transportation fuels, GHG emissions results are aggregated and reported on the basis of total global warming potential (GWP). GHGs are usually converted to a CO\(_2\) equivalent basis using factors recommended by IPCC\(^{(30)}\) (shown in Table 2) or similar factors. Of the 55 studies included in this literature review, 26 reported GHG impacts or GWP. Results from these 26 are shown in Fig. 2. (Not all of them have corresponding ER data shown in Fig. 1.) The studies that reported a range of results for a particular feedstock are designated by vertical bars; studies reporting a single result are designated by a point.

<table>
<thead>
<tr>
<th>Greenhouse Gas</th>
<th>tCO(_2) eq/ t</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO(_2)</td>
<td>1</td>
</tr>
<tr>
<td>Methane (CH(_4))</td>
<td>23</td>
</tr>
<tr>
<td>Nitrous Oxide ((\text{N}_2\text{O}))</td>
<td>296</td>
</tr>
<tr>
<td>CFC-12</td>
<td>10,600</td>
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<tr>
<td>HFC-134a</td>
<td>1,300</td>
</tr>
<tr>
<td>O(_3)</td>
<td>6</td>
</tr>
</tbody>
</table>

The studies shown in Fig. 2 reported GWP as g CO\(_2\) equivalent per MJ of fuel, or other similar value that could be easily converted to this unit. However, some studies investigated the complete WTW lifecycle, while others only included the WTT portion. A frequent assumption, however, is that the carbon emitted during combustion of biofuels is offset by the carbon uptake during the plant’s growth, resulting in minimal net GWP contribution from combustion (there is some minor contribution to GWP due to other pollutants like \(\text{NO}_x\)). This is a significant difference when comparing to GWP of conventional diesel fuel, since a large portion of total life-cycle GHG emissions from diesel fuel occurs during combustion.

Direct comparison among studies is not straight forward, since each study varies in its assumptions and pathways. Nevertheless, Fig. 2 shows a relatively tight range of GWP results, with most values falling between 10 and 60 grams of CO\(_2\) eq. per MJ of fuel produced. The range of conventional diesel GWP values reported in these studies is from 22 to 240 grams of CO\(_2\) eq. per MJ of fuel; this range is not shown in Fig. 2.

The relative GWP difference between biofuel and conventional fuel reported in each study is illustrated in Fig. 3. (Figs. 2 and 3 consist of slightly different sets of studies due to differences in reporting: many studies only reported a percent increase or decrease, while some reported GWP for biodiesel but not for petroleum diesel). When possible, the complete WTW GHG emissions of the biodistillate and reference diesel are compared. The relative impacts of the biofuels varied widely among different studies: several showed a 90% or greater decrease in GHG emissions, while others showed less than 10% benefit. With the exception of Delucchi’s Study No. 38 however, most biodistillate LCA results showed a significant improvement in GWP relative to fossil diesel.\(^{(53)}\) Delucchi’s results demonstrate the potentially severe impacts of \(\text{N}_2\text{O}\) emissions due to land use change.

Figures 2 and 3 also illustrate the large variability in LCA results, even when considering similar feedstocks in similar locations. For example, soybean oil was the feedstock examined for conventional transesterification in 13 of the studies shown in Fig. 2. In all, the reported results ranged from 5.7 to 140 g CO\(_2\) equivalent. When comparing these values to the reported GWP for petroleum diesel (Fig. 3), the variability is even more pronounced. Although the GWP for biodiesel in the NREL study (Study No. 1) was quite high relative to the other soybean LCA cases, it also showed a large benefit relative to petroleum diesel, at about an 80% decrease in GWP. Study No. 46 also showed significant benefits for soy biodiesel at the upper end of its predicted range. Study No. 14 (Hill\(^{(55)}\)) determined a GWP value comparable to that in the NREL Study, but it resulted in a benefit of only about 43% compared to the reference diesel fuel. Similarly, Study No. 30 (Kreider\(^{(56)}\)) and Study No. 28 (Kalnes\(^{(36)}\)) predicted comparable GWP values, but No. 30 resulted in less than 25% reduction in GWP with respect to its reference fuel, while No. 28 showed a 75% decrease. These examples illustrate just some of the significant variability among studies.

Nine studies reported GWP values from renewable diesel life-cycles, with a significant increase in number of publications in recent months (two studies were published prior to 2008, and seven since).
Figure 2: Global warming potential in grams of CO₂ equivalent for 26 studies from 1998-2009

Figure 3: Global warming benefit relative to reference fuel (petroleum) for 31 studies from 1998-2009
When compared to a reference diesel fuel, all renewable diesel LCA studies reported significant GWP benefits (usually 50% or greater). This is seen in Fig. 3 for Studies Nos. 13, 28, 29, 31, 45, 46, 51, 53, and 54. Reports that include gasification to produce DME or FTD are also shown in Fig. 3. These technologies give the most consistent results and show significant potential for reducing GHGs with respect to conventional diesel (Studies No’s. 7, 22 and 34).

Critical Studies for GWP

Besides the critical studies previously discussed for energy return that included GWP, additional studies were identified as critical for GWP based upon similar criteria. The level of detail in the critical studies was enough to provide a breakdown of GWP contributions from each stage of production, as shown in Fig. 4 (Reference diesel fuel values are also shown in Fig. 4 for comparison.) Contributions from each category, as well as total GWP values and reductions relative to fossil diesel, varied significantly. Of the four studies included for soybean methyl ester (SME), two showed comparable GWP reductions relative to the fossil reference fuels used, (No. 1: 79% and No. 44: 71%) although their total GWP levels varied significantly. Similar reductions relative to reference fuels were demonstrated for all three critical studies using rapeseed methyl ester (RME).

Fig. 4 also demonstrates how variations in assumptions during each lifecycle stage contribute to differences in the final GWP results for these biofuels. Contributions from the agricultural stage vary the most. Delucchi’s high N₂O emission rates attribute significant GWP to the agricultural phase, causing a detriment for biodiesel relative to fossil diesel (Study No. 38).

Although the NREL study (Study No. 1) included analysis of GHG emissions, the total inventory was not converted to a CO₂ eq. basis, so the reported GWP depicted in Fig. 4 is based strictly on CO₂ itself, and does not include contributions for N₂O or CH₄. Contributions from the agricultural phase were quite low in this study, but would have been somewhat higher if N₂O and CH₄ emissions had been included. Most of the GWP was attributed to fuel production and final use. The offsets (from CO₂ uptake during plant growth) counteract nearly all combustion emissions. Thus, total life-cycle CO₂ emissions in this study were reduced by nearly 80% relative to conventional diesel.

The Delucchi report (Study No. 38) was considered a critical study because of its attention to soil nitrogen emissions. In Delucchi’s estimation, the contribution of nitrogen emissions during the agricultural phase is large enough to result in a net-negative GWP effect relative to conventional diesel. Besides the major GHG gases (CH₄, N₂O and CO₂), Delucchi’s calculation of total GWP included other trace gases (CFC-12, HFC-134a, and O₃), which further increased the total GWP dis-benefit of biodiesel compared to conventional diesel. The displaced emissions shown in Fig. 4 were from credits to co-products and from CO₂ uptake during plant growth.

Figure 4: Contribution of individual life-cycle stages to overall GWP.
Study No. 44 ((S&T)²(17)) included multiple scenarios for canola oil and soy oil. The baseline scenarios showed that biodiesel from canola resulted in lower GWP than soy, due to its lower nitrogen requirements, and hence lower LUC contributions. The total GWP ranges in Fig. 2, suggest that canola could have a potentially higher GWP than soy oil. However, this was due only to a higher level of detail in the sensitivity analysis for canola. The GWP contribution from combustion was minimal due to carbon offsets already calculated into the final result. The offset shown in Fig. 4 was due to deductions for co-product allocation. Emissions during the agricultural phase were the most significant contribution to the total reported GWP value.

Study Nos. 52 and 53(54,52) are LCA’s published by CARB in support of their LCFS. These are considered critical due to their inclusion of indirect effects. Study No. 52 considered biodiesel from Midwest soy-oil, while No. 53 considered renewable diesel produced via hydroprocessing. Since CARB links CaGREET to the GTAP model to estimate indirect effects, Study No. 52 is one of the few studies to include a specific number for GWP related to indirect effects. The same consideration for indirect effects was not addressed in Study No. 53, although the starting raw feedstocks were identical (soy-oil produced in the mid-west U.S.) The GTAP model produced a single number (42 g CO₂ equivalent) that was added to the GWP result from the LCA study. This appears as a positive offset in Figure 4. The range of numbers for Study No. 52 (in Figure 2) shows the direct effects from the LCA model at the lower limit, and the total of both indirect and direct effects at the upper limit. Study No. 53 shows a single point reflecting only direct effects.

The GWP results for Study No. 8 (Bernesson et al.(37)) demonstrate how allocation method affects the final product. The range in Fig. 2 includes multiple scenarios for different allocation methods and facility sizes for WTT life-cycle. When allocation methods were used, the GWP between small and large scale facilities only changed by about 10%; however, using no allocation of by-products resulted in a 40% difference between small and large facilities. GHG emissions were greatest from small-scale facilities with no allocation of co-products; they were smallest when using the expanded allocation method with large-scale systems. The relative GWP value in Fig. 3 compares results from the large-scale production facility (using physical allocation of co-products) with MK1 diesel oil. This comparison shows a 44% reduction in GWP. If no allocation method were used, the results would show little benefit in GWP, and may in fact result in a dis-benefit. The main contributions to total GWP were agriculture and combustion (Fig. 4). The offset for co-products was already included in the values provided, so does not appear as a separate bar segment in Fig. 4. This study concluded that large-scale facilities provide the best GWP and energy benefits, and that physical allocation methods provide the best-defined inputs.

Study No. 22 (Edwards et al.(21)) compared biodiesel from sunflower and rapeseed oil. As was found with the ER results, sunflower oil also provided greater GWP benefits compared to rapeseed oil. The range of results for each was based on a variety of assumptions for uses of co-products, and from production using methanol or ethanol for transesterification of rapeseed. An updated report for this study was published in November, 2008, and includes additional biodiesel pathways that were not discussed in the original paper. The GWP breakdown for RME when using glycerol as a chemical is shown in Fig. 4 to allow for comparison with a similar breakdown of RME from Study No. 8. This figure shows that the GWP contribution from combustion was nearly completely offset by the assumption of carbon neutrality. Additional offsets from co-product allocation were included in the fuel production phase, resulting in an overall negative GWP contribution for this phase. Therefore, the main contributions to overall GWP were from agricultural activities. Total GWP showed a 46% benefit for RME compared to conventional diesel.

Studies No. 13 (Gartne(50), 45 (Kalnes et al.(40)), and 46 (Huo et al.(53)) were identified as critical LCA studies that included GWP for renewable diesel. The range of values reported in Fig. 2 for Study No. 13 considered rapeseed feedstock from different origins, and fuel production facilities in different locations. The report does not give a relative diesel value, but states that 1.2-2.5 tons of CO₂ equivalent emissions per ton of NExBTL™ are saved relative to petroleum diesel. These values, with the total CO₂ equivalent emissions from each scenario, were used to estimate a relative diesel value of approximately 84 g CO₂ equivalent emissions per MJ of fuel, which was used to calculate the values shown in Fig. 3 and Fig. 4. Fig. 4 shows the GWP breakdown for the Poorvoo scenarios with rapeseed grown on set-aside land. The offsets to GWP were from CO₂ uptake during growth of the feedstock and from co-product allocation (including the use of biogas to power the facility). However, no combustion analysis was included in this study. If GHG emissions from combustion were included, it is likely that the total GWP of the fuel would increase, resulting in a lesser benefit compared to the reference fuel than the 67% figure shown here.

Study No. 45 included scenarios for different feedstocks (rapeseed, palm oil and tallow) for production of both biodiesel and renewable diesel (from the Ecofining™ process). The range of results for palm oil in Fig. 2 included only a high and low value, corresponding to use of biogas or not. Figure 3 shows that the production of renewable diesel had greater GWP benefits than biodiesel for all feedstocks. Tallow had the lowest GWP because it was considered a waste product; having no significant GHG inputs. Thus, tallow-derived renewable diesel showed a 95% decrease in GWP relative to conventional diesel. Figure 4 shows the GWP breakdown for production of both biodiesel and renewable diesel from rapeseed. The offsets for each were already included in the calculations for total GWP,
so are not shown here as separate bar segments. The amount of CO₂ emitted during oil production was slightly larger for biodiesel than for renewable diesel, but the amount of GWP resulting from fuel manufacturing was slightly higher for renewable diesel. Renewable diesel, however, had a lower overall GWP than biodiesel for all feedstocks.

Study No. 46, as discussed above, included scenarios for biodiesel, and renewable diesel produced using both the Ecofining™ process and the SuperCetane™ process. The range of values shown in Figure 2 reflects the results from each of the allocation procedures for the three production methods. The displacement and hybrid methods for the SuperCetane process resulted in an offset to GWP. This range for the SuperCetane™ process was much greater than for biodiesel or Ecofining™ due to the large number of co-products that were generated. Both the energy and market value allocation methods resulted in similar GWP values for each of the three production methods.

Additional details on other studies in the above figures are presented in the Appendix.

OTHER COMMON IMPACT CATEGORIES

In addition to GWP and energy requirements, other ecological or resource impacts are often assessed using LCA methodologies. Some other categories that are occasionally included in biodiesel LCA studies are discussed briefly below, along with a description of results from the studies in which they were included.

Water Resources

Biodiesel production requires water during both growth of the feedstock and the esterification process. Although water is an important resource, it is not frequently included in biodiesel LCA, likely because of the many uncertainties and regional specificities of water use for biofuel feedstocks. Additionally, it is believed that increased agricultural production of biofuels will not substantially increase the national water-use, although it may have local impacts on already stressed water resources. Only two of the literature sources explicitly included water use. Sheehan et al. (Study No. 1[25]) found that water use from soybean-derived biodiesel was three times higher than petroleum diesel. However, they also found that wastewater generation was roughly 5 times higher for petroleum diesel than for biodiesel (0.175 L/MJ compared to 0.037 L/MJ, respectively), which has implications for additional environmental impacts. Another U.S. study by Kreider et al. (Study No. 30[26]) found that biodiesel production required about 25 L of water/MJ of fuel, while conventional diesel only required 0.018 L/MJ.

Eutrophication

Eutrophication occurs as a result of excess nutrients (phosphorous and nitrogen) in agricultural applications which runoff into water supplies. In a nutrient-rich environment, plants such as algae grow and decay at a more rapid rate, causing reductions in water quality, including hypoxia (dead zones) in the Chesapeake Bay, the Gulf of Mexico, and elsewhere. The eutrophication potential (EUP) is commonly measured in agricultural LCAs, and is sometimes included in biodiesel LCAs. High EUP results have been reported for biodiesel compared to conventional diesel.[37,21,46] However, one report indicated that biodiesel produced from organic crop growth reduced EUP compared to conventional diesel.[58] Additionally, using waste products such as waste vegetable oil provided an EUP benefit relative to conventional diesel.[56]

Acidification

The acidification potential (ACP) has also been shown to increase slightly for biofuels. Acidification results when nitrogen, sulfur oxides, and ammonia that are released during fertilization and plant growth stages are oxidized in the atmosphere to form acids. This can lead to “acid rain” which lowers the pH of soils and water. Since these types of emissions are only associated with agricultural activities, biodiesel fuels generally show an increase in ACP compared to petroleum diesel.[56,21,24] Again, use of waste vegetable oils and organic cropping methods can reduce these effects.[38,56]

Photochemical Ozone Creation Potential

A handful of studies included additional environmental impact categories. Although Photochemical Ozone Creation Potential (POCP) is an important environmental impact, it is rarely assessed. POCP, which relates to smog formation, increases due to ozone formation from NOx and hydrocarbon emissions during incomplete combustion. Three studies have reported that biodiesel shows a small POCP benefit relative to diesel fuel.[56,37,38] However, considering the high variability of results in the biodiesel emissions literature,[60] a definitive conclusion about POCP benefits cannot be reached.

Other Impact Categories

Additional LCA impact categories include abiotic depletion, ozone layer depletion, human toxicity, waste, fresh water aquatoxicity, and habitat disruption. These categories are rarely reported in the literature. A small benefit for abiotic depletion for biodiesel was reported by Niederl.[38] An increase in ozone layer depletion for biodiesel relative to conventional diesel was reported by Gartner.[56] Harding et al.[61] reported values for abiotic depletion, ozone layer depletion, human toxicity and aquatoxicity, but did not relate them to a reference fuel. A recent report for the California Environmental
Protection Agency summarized numerous environmental issues associated with the transport and fate of biodiesel, though most of those issues were not addressed on a life-cycle basis.\(^{(62)}\)

**CONCLUSIONS**

Life-cycle assessments (LCA) of “well-to-wheels” energy inputs and GHG emissions are now recognized as important tools for understanding the relative benefits of biodistillate fuels compared to conventional fuels. However, LCA models are very data intensive, and require numerous inputs having high uncertainty. Some of the most critical inputs are in areas that are most uncertain – such as assumed agricultural practices and their emissions, impacts attributed to co-products, and land use changes (LUC).

Variations in LCA model assumptions have drastic effects on the final results. Consequently, it is difficult to compare directly LCA results from different studies. Comparison of relative effects between biofuel and conventional fuel scenarios conducted within the same study is often more informative.

Life-cycle energy results are typically reported as energy return on investment (EROI, or more simply, ER), meaning the heating value of the final biofuel divided by the total fossil energy inputs involved in producing, distributing, and using the fuel. Typically, ER values for conventional diesel fuel are slightly under 1.0. Analysis of numerous LCA studies reported in the literature gave an overall average ER value of about 3.1 for biodistillates, indicating substantial benefits for these fuels (both biodiesel and renewable diesel) in terms of life-cycle energy.

LCA results for GHG emissions are usually expressed in terms of relative global warming potential (GWP). In almost every published LCA study, biodistillate scenarios resulted in lower GWP compared to conventional diesel. In approximately 40 studies investigated here, the GWP benefits of the biodistillate fuels ranged from 10% to 90%, with an overall average value of about 60%. However, there are a few exceptions, mainly due to assumptions of high N\(_2\)O emissions, where biodiesel scenarios showed overall GWP dis-benefits compared to conventional diesel.

**ACKNOWLEDGMENTS**

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

ACP  Acidification potential
Ag   Agriculture
ALCA Attributional life cycle assessment
ARGOS Agriculture Research Group on Sustainability
B100 Neat (100%) biodiesel
B20 Blend of 20% biodiesel in petroleum diesel
BEES Building for Environmental and Economic Sustainability
BESS Biofuel Energy Systems Simulator
BD   Biodiesel
BTL  Biomass-to-liquids
BTU  British thermal unit
CaGREET California- modified GREET
CARB California Air Resources Board
CD   Conventional Diesel
CDV  Conventional Diesel Vehicle
CLCA Consequential life cycle assessment
CO2  Carbon dioxide
CPA  Co-product allocation
CRC  Coordinating Research Council
DME  Dimethyl Ester
EBAMM ERG Biofuel Analysis Meta-Model
EE   Energy Efficiency
EI   Environmental Impacts
EIO-LCA Economic Input/ Output Life Cycle Assessment
EISA Energy Independence and Security Act
EPA  U.S. Environmental Protection Agency
ER   Energy Return
ERMI Energy return on investment (also called ER)
EU   European Union
EUP  Eutrophication potential
FAPRI Food and Agriculture Research Policy Institute
FASOM Forest and Agricultural Sector Optimization Model
FE   Fossil Energy
F/S  Feedstock
FTD  Fischer Tropsch diesel
g CO₂ eq Grams CO₂ equivalent based on IPCC factors
GD   Green Diesel
GEMIS Global Emission Model for Integrated Systems
GHG  Greenhouse gas
GREET Greenhouse gases, Regulated Emissions, and Energy use in Transportation model
GTAP Global Trade Analysis Project
GTL  Gas-to-liquids
GWP  Global Warming Potential
HDDV Heavy-duty diesel vehicle
HV   Hybrid vehicle
HVO  Hydrotreated vegetable oil
ICE  Internal combustion engine
ILUC Indirect Land Use Change
IPCC Intergovernmental Panel on Climate Change
ISO  International Organization for Standardization
kg   kilogram
LCA  Life-cycle assessment
LCFS Low Carbon Fuel Standard
LEM  Life Cycle Emissions Model
LUC  Land Use Change
MJ   Mega-joule
MMT  Million metric tons
MPO  Malaysia Palm Oil
N    Nitrogen
N₂O  Nitrous oxide
NO₂  Nitrogen dioxide
NOx  Oxides of nitrogen
NREL National Renewable Energy Laboratory
O₃   Ozone
OS   Overseas
OZD  Ozone Depletion Potential
PD   Petroleum Diesel
POCP Photochemical ozone creation potential
RD   Renewable Diesel
REE  Rapeseed ethyl ester
RME  Rapeseed methyl ester
SAE  Society of Automotive Engineers International
SME  Soy methyl ester
SVO  Straight vegetable oil
TTW  Tank-to-wheels
ULSD Ultra-low sulfur diesel fuel
UVO  Used Vegetable Oil
WTW  Well-to-wheels
WTT  Well-to-tank
WVO  Waste vegetable oil
2G   Second Generation Biodiesel.

Biodistillate: Any mid-distillate fuel (diesel fuel, kerosene, jet fuel, or heating oil) produced from recently living plant or animal materials by a variety of processing technologies.

Hydroprocessing: Range of refinery processes involving catalytic treatment of feedstocks in the presence of hydrogen.

Renewable Diesel: Non-fossil hydrocarbon fuel produced by catalytic hydroprocessing of triglycerides from vegetable oils or animal fats. Synonymous with Green Diesel.

Transesterification: Chemical process involving reaction of triglycerides with an alcohol (usually methanol) to produce biodiesel and glycerol.

Second Generation Fuels: Fuels produced from non-food feedstocks (such as jatropha, algae, and lignocellulose) by any processing technology, or from edible feedstocks using advanced conversion processes (such as catalytic hydroprocessing).
<table>
<thead>
<tr>
<th>Study No; Ref No; Year</th>
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<th>Summary of Paper</th>
<th>Critical Assumptions</th>
<th>No. of Scenarios Method of Co-Product Allocation and LUC considerations</th>
<th>Reference Fuel</th>
<th>GWP*/ Change in GWP relative to conv. Diesel g CO₂/MJ</th>
<th>EROI**</th>
<th>Other considerations***</th>
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<td>1 (E,G,R) 1998</td>
<td>USA; Soybean: Trans-est. (WTW) LEM</td>
<td>Often cited early LCA of B100 and B20 for national averages scenarios compared to PD. Sensitivity analysis included, showing robust results with ER and GWP benefit for BD.</td>
<td>• Avg for 14 soy producing states. • EE of BD-vehicles are identical to CDV. • C-neutral principle. • avg. Transp. dist. 571 mi.</td>
<td>1 with investigation of FE and primary energy using Mass CPA. Direct LUC in cultivation inputs.</td>
<td>PD: GWP: 235.9 EROI: 0.833 Primary and FE.</td>
<td>WTW (not incl. tailpipe emissions gm CO₂ only) B20: 198.9 B100:50.9</td>
<td>Biodiesel: 0.806 (Primary Energy) 3.215 (Fossil Energy) Wastewater production (L/MJ) CD: 0.175 B20: 0.147 B100: 0.0369</td>
<td></td>
</tr>
<tr>
<td>2 (32) 2002</td>
<td>USA; Soybean: Trans-est. (WTW &amp; WTW) LEM</td>
<td>Provides overview of updates to LEM specific assumptions including higher than most conversion rates for N₂O from N₂ fertilizers.</td>
<td>None; Uses combo of expansion and displacement; Direct LUC in cultivation. Heavy consideration of N rates.</td>
<td>None</td>
<td>None</td>
<td>No results, but discusses negative GWP for biodiesel relative to PD due to N rates.</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>3 (83) 2002</td>
<td>Europe; Rapeseed Trans-est. LBST E2database for WTT and GM for TTW</td>
<td>Both WTT and WTW analysis of a variety of renewable/alternative fuel pathways. Only blends of B5 (RME) with petroleum diesel are included.</td>
<td>None discussed</td>
<td>PD : WTT: ER=.89 GHG=11 WTW in CDV &amp; HV Energy=1.84-2.19 MJ/km GHG:140-166 g/km</td>
<td>WTT: 8+/: 2.5 g/MJ WTW: 1.95-2.31 MJ/km (0% change relative to reference)</td>
<td>WTT=.85 all. 0.93 fossil. WTW: 1.95-2.31 MJ/km (increase from CD)</td>
<td>None</td>
<td>None; not included in figures since results for B5 blend only are given.</td>
</tr>
<tr>
<td>4 (84) 2003</td>
<td>So. Italy; Rapeseed Crop Production only Not mentioned</td>
<td>Investigated use of B. Carinata for BD production in comparison to the more common B. napus in mid-west Italy. Only crop growth.</td>
<td>• 100 km distances data inputs from literature • no co-product allocation</td>
<td>None, no CPA.: comparison of different cropping methods and productivity.</td>
<td>None discussed</td>
<td>None discussed</td>
<td>Energy requirement to product crop only.</td>
<td>None</td>
</tr>
<tr>
<td>5 (68) 2003</td>
<td>Germany; Rapeseed: Trans-est. (WTW) IFEU</td>
<td>Overall comparison of RME w/ C; incl. increase in availability of co-products for use.</td>
<td>• Ag assumptions calculated under average German conditions. • Base case processing</td>
<td>One w. expanded CPA incl. rapeseed honey and meal fermentation to produce biogas. No LUC—ref. is set-aside land w/ fertilizers.</td>
<td>Diesel</td>
<td>2.2 kg CO₂ eq / Liter RME saved (compared to that emitted in 6L of CDI)</td>
<td>Saves energy required to produce 8L of CD.</td>
<td>CD advantage for ACP, Nutrient inputs, and OZD. Small POCP benefit for RME.</td>
</tr>
<tr>
<td>6 (E) 2003</td>
<td>EU- Italy; Sunflower, Rapeseed, Soybean: Trans-est. (WTW) Not-mentioned</td>
<td>Investigated 3 F/S with ranges of crop yield and co-product allocation. To determine if it falls within sustainable ag practice</td>
<td>• Ranges of crop yields are EU average</td>
<td>Ranges for 3 F/S; w. or w/o. CPA and range of crop yields. Allocation likely by energy. Direct LUC by crop yield and fertilizer inputs.</td>
<td>Comparison of results and to ethanol produced from lignocellulose and traditional F/S.</td>
<td>N/A</td>
<td>w.: w.o. Allocation Sunflower: 0.4-1.2; 0.3-0.9; Rapeseed: 1.0-1.5: 0.7-1.0; Soybean: 0.7-1.6: 0.2-0.6;</td>
<td>None</td>
</tr>
<tr>
<td>7 (R) 2004</td>
<td>Germany—Farmed wood; Choren Process—DIN EN ISO 14040</td>
<td>Summary of 3 scenario LCA on SunDiesel produced via the Choren Process (gasification for FTD) based on data from a plant in Freiburg.</td>
<td>• Based on data for 43MW Choren process plant in Freiburg (under construction when published)</td>
<td>3 scenarios for H₂ prod; CPA not discussed. For self sufficient/ future and partial self-sufficient. LUC not discussed</td>
<td>CD:No value given; other impacts are relative.</td>
<td>GWP 91% , 87% and 61 % less compared to CD</td>
<td>Efficiency of Process 64%, 45%, 55%</td>
<td>Efficiency: 29%, 13%, 3% (ACP: 42% 27% 5% (rel to CD))</td>
</tr>
<tr>
<td>Study No.</td>
<td>Ref No.; Year</td>
<td>Location; Feedstock; Production Pathway; LCA tool used</td>
<td>Summary of Paper</td>
<td>Critical Assumptions</td>
<td>No. of Scenarios Method of Co-Product Allocation and LUC considerations</td>
<td>Reference Fuel</td>
<td>GWP**/ Change in GWP relative to conv. Diesel g CO₂/MJ</td>
<td>EROI**</td>
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<td>8</td>
<td>(E,G,R) 2004</td>
<td>Sweden; Rapeseed Trans-est. (WTI) Not mentioned</td>
<td>A limited LCA to assess the EI of small-, medium- and large-scale production systems with investigation into 4 methods of CPA</td>
<td>Rapeseed species is Brassica napus 40 ha, 1000 ha, and 50,000 ha for sm, med and lg. Lg scale--high extraction eff., long dist. Sm-low extraction eff., short dist. Yield: 2670 kg/ha yr w. 45% oil • electricity: 48% hydro, 44% nuclear, 4% fossil fuels, 3% biofuels BD-LHV = 38.5MJ/kg Twelve: 4 types of co-product allocation: (energy, economic, none, expansion) for small, medium or large scale production facility. Direct land use change from agriculture</td>
<td>Comparison between large-scale facility w/ physical allocation to lit. values for MK1 diesel oil. GWP: 217 g CO₂/ MJ engine (vs. 127)</td>
<td>sm, med, lg- resp.: Physical allocation: 40.3, 39.5, 40.2</td>
<td>sm, med, lg- resp.: Physical allocation: 40.3, 39.5, 40.2 Economic allocation: 51.1, 49.1, 45.8</td>
<td>None: 1.8, 2.0, 2.5</td>
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<tr>
<td>9</td>
<td>(E,G,R) 2004</td>
<td>Italy; (WTI) Soybean: Trans-est. Based on Emergy analysis by Odum HT</td>
<td>Use of BD in boilers and diesel engines when compared with diesel oil. Provides test results and LCA.</td>
<td>Soy-harvest: 2445 kg/ha • fuel use 80, 43, 51kg/ha for N, phosphates, and K, resp.: 65% of emissions from combustion process. 2: CPA by mass vs. none.</td>
<td>Commercial Diesel Oil D2. GWP= 22.2 3.4, 3.6, 3.5 (12-75% reduction) (Incl. combustion)</td>
<td>sm, med, lg- resp.: Physical allocation: 40.3, 39.5, 40.2 Economic allocation: 51.1, 49.1, 45.8</td>
<td>sm, med, lg- resp.: Physical allocation: 40.3, 39.5, 40.2 Economic allocation: 51.1, 49.1, 45.8</td>
<td>None: 1.8, 2.0, 2.5</td>
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<tr>
<td>10</td>
<td>(E) 2004</td>
<td>Lithuania: Rapeseed : Trans-est. (WTI) Independent using ISO 14040-14049</td>
<td>Energy LCA of RME &amp; REE for different production, processing, levels of ag-yield, &amp; CPA. Goal is EU value of ER = 1.9; only thru REE using EE high-productivity transest. and at least 3 t/ha yield. Currently Lithuania avg 1.8 t/ha rapeseed.</td>
<td>Ag inputs incl. fuel and fertilizer use. Data are specific to Lithuania Two different ag methods: (1) mineral fertilizers and drying of seed, (2) biofertilizers and seed preservation. Forty: methanol vs. ethanol as process fuel; harvest yield; different ag methods; productivity high with hot pressing or low with cold pressing. LUC not discussed.</td>
<td>Fossil Diesel 0.885 (presented for comparison)</td>
<td>sm, med, lg- resp.: Physical allocation: 40.3, 39.5, 40.2 Economic allocation: 51.1, 49.1, 45.8</td>
<td>sm, med, lg- resp.: Physical allocation: 40.3, 39.5, 40.2 Economic allocation: 51.1, 49.1, 45.8</td>
<td>None: 1.8, 2.0, 2.5</td>
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<tr>
<td>11</td>
<td>(E) 2005</td>
<td>No location; Soy &amp; Sunflower; Trans-est. WTI; lit data.</td>
<td>Energy/ cost analysis of soy and sunflower oil transest. Producing biodiesel from soy and sunflower results in a negative fossil energy impact.</td>
<td>Sunflower has lower yield than soy (1500kg/ha vs 2668 kg/ha) but higher oil yield (26% vs 18%) Soy: LHV = 37.7 MJ/kg. With and without Soy meal by energy, and w and w/o &quot;soy meal&quot; from sunflower prod. No glycerine credit. LUC not discussed, but energy of fertilizers is incl.</td>
<td>Biodiesel: Compares cassava ethanol relative to biodiesel.</td>
<td>sm, med, lg- resp.: Physical allocation: 40.3, 39.5, 40.2 Economic allocation: 51.1, 49.1, 45.8</td>
<td>sm, med, lg- resp.: Physical allocation: 40.3, 39.5, 40.2 Economic allocation: 51.1, 49.1, 45.8</td>
<td>None: 1.8, 2.0, 2.5</td>
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<td>12</td>
<td>(G) 2006</td>
<td>Guangxi region of China; Cassava: Ethanol production* Not mentioned</td>
<td>Comparative analysis of ethanol produced from cassava in China. Compares to BD results of 1998 NREL study. Shows fuel is less efficient than BD of NREL study.</td>
<td>No pathway for biodiesel: ethanol production compared to results of 1998 NREL study for biodiesel.</td>
<td>Biodiesel: Compares cassava ethanol relative to biodiesel.</td>
<td>sm, med, lg- resp.: Physical allocation: 40.3, 39.5, 40.2 Economic allocation: 51.1, 49.1, 45.8</td>
<td>sm, med, lg- resp.: Physical allocation: 40.3, 39.5, 40.2 Economic allocation: 51.1, 49.1, 45.8</td>
<td>None: 1.8, 2.0, 2.5</td>
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<tr>
<td>13</td>
<td>(E,G,R) 2006</td>
<td>Porvoo Finland— Rapeseed and Palm oil: NExBTL process--hydro treating WTT IFEU</td>
<td>Energy and GHG of production of NExBTL compared to CD for scenarios at plant in Porvoo, Finland. Shows NExBTL has advantage for energy and GHG relative to CD. LHV of NExBTL = 44 MJ/kg.</td>
<td>Data from Porvoo plant Finland vs EU Electricity split and, rapeseed from EU and overseas (OS), Palm from Malaysia (MPo) and other int’n1 mkt. Same scenarios as Porvoo for rapeseed. All feedstock transp. to central EU. 6: diff F/S and F/S origins. CPA is rape meal substitution of soy meal from N. America. Looks at both natural and set-asde land for crop growth in both Europe (EUN and EUSA) and overseas (OSN and OSSA) Rapseed vs. CD: GWP: saves 1.2-2.5 t CO₂ eq/ t of NExBTL (33-69%) EROI: 30-33-GJ primary energy saved per t NExBTL (61-68%) MPO in ref. to different L.U.</td>
<td>Rapseed EUSA: 30.0 EUN: 44.7 OSN:56.4 Palm:53.4; Food Oil: 33.2 Coconut:62.0 Reduction: (1 CO2 eq per t NExBTL Rapseed: 1.2-2.5 MPO: 1.4</td>
<td>sm, med, lg- resp.: Physical allocation: 40.3, 39.5, 40.2 Economic allocation: 51.1, 49.1, 45.8</td>
<td>sm, med, lg- resp.: Physical allocation: 40.3, 39.5, 40.2 Economic allocation: 51.1, 49.1, 45.8</td>
<td>None: 1.8, 2.0, 2.5</td>
</tr>
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</table>

**GWP** - Global Warming Potential

**EROI** - Energy Return on Investment

***Other considerations*** - Additional notes or considerations for each study.
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>14</td>
<td>US; Soybean: Trans-est. WTT Not mentioned</td>
<td>LCA determination of biodiesel from soybean and corn ethanol in the US—shows biodiesel provides advantage over both diesel and ethanol.</td>
<td>Boundaries include energy to grow seed; produce farm machinery and buildings; and, sustaining farmers' households.</td>
<td>CPA: no credit, by mass, by economics, and by energy. 2 types of ER. Direct LUC/ release of GHG from fertilizers of land already in production.</td>
<td>Diesel: GWP: 82.3 (41% reduction)</td>
<td>Energy gain 2.9%</td>
<td>GWP= 49</td>
<td>No credit: 1.16; Mass: 1.83 Econ: 1.81 Energy: 3.38 ER (energy in biodiesel alone)= 3.67</td>
</tr>
<tr>
<td>15</td>
<td>Austria; Tallow and UVO: Trans-est. WTT EcoIndicator 99 database</td>
<td>BD from genuine waste material UVO. 3 scenarios based on the origin of the UVO. Results in GWP benefit to biodiesel; also has lower impacts (EUP,ACP, POCP, ABD) than biodiesel from waste (e.g RME).</td>
<td>Results discussed for Scenario I for UVO only.</td>
<td>Three: origin of UVO with mass and economic allocation methods. LUC not considered</td>
<td>Fossil Diesel: GWP: 90 (80% reduct.) EUP=0.225 ACP=0.23 ABD=0.054 POCP=0.019</td>
<td>GWP= 18</td>
<td>None</td>
<td>EUP: 0.033; ACP: 0.21; ABD: 0.037; POCP: 0.012</td>
</tr>
<tr>
<td>16 Larson  (E.G.R) 2006</td>
<td>Summary of different publications.</td>
<td>Details different biofuel-LCA pubs to determine significance of differences in assumptions and results. Describes 4 BD-LCA references, 4 on FTD or DME, and others for bioethanol and biomass production systems.</td>
<td>Different methods discussed: weight, energy, process energy, economic, displacement. Details of each paper included are not discussed herein.</td>
<td>Soil carbon and nitrogen conversion are considered important topics for differences in final results.</td>
<td>Petroleum diesel referenced in other papers.</td>
<td>Numbers are all referenced in other papers.</td>
<td>Numbers are all referenced in other papers.</td>
<td>Discussion of vehicle assumptions being critical to final results.</td>
</tr>
<tr>
<td>17 Nelson &amp; Schrock (E) 2006</td>
<td>US; Tallow; Transest.; WTT</td>
<td>An evaluation of energy inputs for the production of tallow-based BD. The study has shown the selection of system boundary and the allocations of energy input to co-products have significant effects on the LCA results.</td>
<td>Animal feed and cattle data based on USDA publications for natl avg practices. Meat processing data are obtained from plants in Kansas. Total energy incl. direct energy input and energy in raw material manufacture, i.e. fertilizer synthesis.</td>
<td>3: tallow is (1)a waste product, carrying no upstream energy use; (2) a co-product, but the energy input in feed production is not considered; (3) feed production is incl. CPA is based on mass, market values, or by displacement.</td>
<td>None.</td>
<td>Carbon intensity for biodiesel fuel is not evaluated in the study</td>
<td>Energy ratios are 5.9 to 17 if tallow is treated as a waste, 3.5 to 5.7 if meat processing is included, and 0.81 to 0.89 if energy input for animal feed production is incl.</td>
<td>Data of criteria pollutants emissions at the exhaust for hydrogenated oils are included in the study</td>
</tr>
<tr>
<td>18 Koyama et al R 2007</td>
<td>Palm oil (Origin not specified); Hydrogenation/stand alone process and transest; WTW</td>
<td>The paper presents LCA results for palm oil BD (POBD) and hydrogenated palm oil (HPO). Both biofuels show less GHG emissions compared to CD.</td>
<td>No details are given.</td>
<td>None presented.</td>
<td>Petroleum diesel</td>
<td>The relative GHG emissions for HPO and POBD are both about 60% less than CD.</td>
<td>None.</td>
<td>Data of criteria pollutants emissions at the exhaust for hydrogenated oils are included in the study</td>
</tr>
<tr>
<td>19 Barber et al (E.G.R) 2007</td>
<td>New Zealand; Tallow; Transest; WTW; ARGOS database</td>
<td>A full LCA of energy and GHG emissions for tallow biodiesel covering the animal production, meat processing and rendering, and the refining of tallow into biodiesel. The study indicated tallow biodiesel has lower carbon intensity than conventional petroleum diesel.</td>
<td>A farm model: 44% sheep / 56% cattle. Avg energy intensity for animal prod. and meat processing is 14.6 MJ/kg carcass before allocation. CPA to meat, hides, offal and raw render material (including 17-22% tallow). Total energy consumption for tallow BD plant is 23.0 MJ/kg w.o CPA</td>
<td>CPA are based on market values for the entire LCA. Sensitivity analysis is primarily performed for variations in the price for the co-products.</td>
<td>Petroleum diesel ER=.84 GWP = 82.55</td>
<td>Total GHG emissions for tallow biodiesel are 42.6 gCO₂e/MJ; Relative GHG reduction is 50% compared to petroleum diesel.</td>
<td>Energy ratio is approximately 2.</td>
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<td>20 (E,R) 2007</td>
<td>Italy; Rape and sunflower seed; Trans-est. WTT</td>
<td>Not mentioned</td>
<td>Comparison of 3 most promising bio-energy incl BD from oil crops; incl. bioethanol and electricity. ER can be increased if straw can be used for power generation. CPA increases output/input energy ratios.</td>
<td>Four: co-product allocation by economics vs. none of two feedstocks. Direct land use cultivation is considered for energy effects-- no emissions calculations.</td>
<td>Comparative between types of biofuel energy.</td>
<td>None</td>
<td>1.3-1.4 – w/o co-products 2.1-1.9 - with co-products Rape= 10.31 Sunflower= 10.17 w/ co-products Rape= 24.96 Sunflower= 28.08</td>
<td>Energy GJ/ha NET)</td>
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<tr>
<td>21 (R) 2007</td>
<td>Sweden; Rapeseed; Trans-est. (WTT) Not mentioned</td>
<td>Short article describing LCA research by Northeast Biofuels.</td>
<td>Not mentioned</td>
<td>One; allocation method not discussed LUC not mentioned</td>
<td>Conventional low-sulfur diesel.</td>
<td>94% reduction</td>
<td>None</td>
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<tr>
<td>22 (E,G,R) 2007</td>
<td>EU; BD: Trans-est. of Rapeseed and Sunflower Gasification to DME or syn-diesel of wood-waste (WW), farmed wood (FW), or waste wood via black liquor (BL)*; LBST.</td>
<td>Incl WTT, TTW and WTW of many alt. fuels. BD study incl. RME vs. REE and SME. Also incl. syn-diesel and DME from NG, Coal and Wood. BD study results: use of grazing/ forest land for planting in near-term has dis-benefit. Advanced biofuels could subst. fossil fuels, but potentially higher energy and economic cost. 2G has high GHG savings, but high energy cost. DME has best overall.</td>
<td>• Commercially available tech in 2010-2020 • Energy on LHV basis • Fertilizer and farming input data from FIE 1998, which has higher N₂ rates than EU25, but higher yields. • 85% efficiency for process estimated/ depends strongly on performance of FT catalyst • Wood conversion processes are made electricity neutral. • Vehicles in WTW are 2010-2020</td>
<td>Conventional Diesel (and other types of alternative fuels) GWP = 88 g CO₂eq / MJ fuel (including combustion for comparison) EROI= 0.863 GWP values WTT Glycerin as chem. RME=46.5 /48.0 REE=43.3/ 45.2 SME=24.7 /26.6 as animal feed RME= 51.8/ 53.7 REE =48.0/ 49.7 SME= 30.0 /31.6 Before/After comb-DME : Syn-Diesel WW:4.5/4.8; 4.8/5.7 FW: 7.0/8.1; 7.4/8.5 BL:2.2/3.5; 2.4/3.4</td>
<td>Glycerin as chem.; RME =2.17 REE=2.44 SME= 2.78 as animal feed RME=1.96 RE = 2.22 SME= 2.44 DME (incl. E final fuel) WW:16.7 / -- FW: 16.7 / 356 BL: 33.3 / 269 SynDiesel WW: 14.3 / -- FW:16.3/ 385 BL: 25 /350</td>
<td>Economic estimation included. Brief paragraph of threat of increase EUP and ACP potential for biodiesel and lowering of watertable. No calculations.</td>
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<td>23 (R) 2007</td>
<td>USA; Average mix of soybean and yellow grease; Trans-est. WTT GREET</td>
<td>Brief brochure on the importance of full fuel LCA. Comparison between different alternative fuel types. Cellulosic ethanol also decreases CO₂ by 91%</td>
<td>Average mix of soybean and yellow grease, same as analysis completed for the Renewable Fuel Standard. Uses GREET default for electricity mixes, etc.</td>
<td>Scenarios not discussed Indirect land use change not included in GREET. Cultivation included.</td>
<td>Diesel</td>
<td>67.7 % decrease in CO₂</td>
<td>None</td>
<td></td>
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<tr>
<td>24 (R) 2007</td>
<td>Canada; Canola, Tallow; Wood: Trans-est., Gasif. to FTD Super-Cetane (WTW) GGHGenius</td>
<td>23 fuel-vehicle pathways were considered to test viability of each and make policy recommendations; 4 are for biodiesel specifically. Next gen. have high GHG reduction potential.</td>
<td>None discussed</td>
<td>None discussed</td>
<td>Conventional fuels and other alternative fuels to determine best option.</td>
<td>N/A</td>
<td>None discussed</td>
<td></td>
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<tr>
<td>25 (R) 2007</td>
<td>The Netherlands; None for biodiesel WTW Swiss Ecoinvent V1.1 data</td>
<td>A quick scan LCA to elaborate on different allocation scenarios (economic, physical and ecoinvent default) for multi-output processes for average Dutch passenger car-show large differences in LCA results.</td>
<td>None discussed for biodiesel Different allocation methods and allocation coefficients LUC not discussed</td>
<td>None: comparison of allocation methods w/o assessment of results.</td>
<td>N/A</td>
<td>Does not assess total values</td>
<td>None</td>
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<td>26 (E,G,R) 2007</td>
<td>Sweden; Rapeseed : Trans-est. WTT Matlab/ Simulink, with ISO-14040</td>
<td>LCA of RME, ethanol and biogas produced from processing raw material from an organic farm in industrial scale plants for use on the farm to make it self sufficient.</td>
<td>• 25km transport distance between farm and plant • 1000 ha cultivated • Includes fuel usage in farm equipment, emissions assumptions for farm equipment provided. WTT, zero emission during combustion = WTT.</td>
<td>Two: co-product allocation by economics vs. none. Direct land use only.</td>
<td>Conventional Diesel. Also, comparison of ethanol and biogas use. GWP: 79.5</td>
<td>21.8</td>
<td>With/ Without Allocation 8.3 / 4.2</td>
<td>EUP: 28.46 kg O₂/ eq/ MJ fuel (79% increase) ACP: 0.827 (31% increase) 8.5% of 1000 ha or land used for fuel prod. Economic: .047 Euro for RME</td>
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<tr>
<td>27 (G) 2007</td>
<td>Location not discussed; Rapeseed: Trans-est. SimPro V6.</td>
<td>5 cases of 1000kg biodiesel production from different catalyst types (NaOH or biological enzyme Candida antarctica), use of ethanol or methanol, and efficiency of alcohol recovery.</td>
<td>• Process plant and equip construction not incl. • Alcohol to oil ratio from 3:1-6:1• Variety of process-based diff/assump. • Biological catalyst data from lab exp. • Cases: 1: NaOH cat, MeOH, HR. 2: Biocat, MeOH, 3: NaOH, MeOH, LR 4) NaOH , EIOH, LR 5) bio-cat, EIOH</td>
<td>None: comparison of catalysis methods and other process differences.</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>(gm eq/ MJ fuel) EUP: 1.37-1.39 ACP 1.08-1.17 ABD : .494-.664 OZD: 2.0E-5-3.3E-5; HT: 4.95-6.79; HZO tox: .458-1.55</td>
</tr>
<tr>
<td>28 (E,G,R) 2007</td>
<td>Western Europe; Soybean : Eni Ecofining WTT ISO 14040 with data from SimaPro.</td>
<td>LCA of Ecofining (hydro-treating) soy oil. Two scenarios for different H₂ production. GD compares favorably to biodiesel, reducing fossil energy by 84-90% when H₂ is produced from by-products.</td>
<td>• Data from NREL study (#1) incl. cultivation, harvesting, and extraction w/ intermed. transp steps. • Transp. to end user is omitted • # A: H₂ is typical refinery blend. # B: H₂ from GD by-products propane and naphtha</td>
<td>Two: method of H₂ production. Allocation method by mass. LUC not discussed but N₂O emissions are neglected.</td>
<td>Diesel and Biodiesel. GWP 85.6 EROI: 0.78</td>
<td>BD= 23.6 GD A=14 GD B=12.7 Improvement BD = 82 (82%); 72.4% GD A= 71.6 : 83.6% GD B= 72.9 : 85.1%</td>
<td>BD= 3.0 GD A=3.4 GD B=5.0 From Palm Oil: BD D= 4.0 GD A=5.0 GD B=7.7</td>
<td>None</td>
</tr>
<tr>
<td>29 (R) 2007</td>
<td>US; Soy oil: Conoco Philips-hydro treating WTT Not mentioned</td>
<td>Presentation of results of LCA study of renewable diesel from soybean oil compared to Biodiesel and Petroleum diesel</td>
<td>Not discussed</td>
<td>Summary of hydrotreating/ renewable diesel technologies LUC not discussed</td>
<td>Petroleum Diesel COP soy 56% UOP soy 74% NExBTL rape 69%</td>
<td>Not discussed</td>
<td>Not discussed</td>
<td>None</td>
</tr>
<tr>
<td>30 (E,G,R) 2007</td>
<td>US (Colorado); Soybean : Trans-est. WTT Not mentioned</td>
<td>Study investigating potential future fuels and their sources to determine the most sustainable direction for US transportation fuels.</td>
<td>Not described in detail • Delucchi and Lippmann CO₂ emissions data • Emissions include driving cycle • consumption of CO₂ by photosynthesis not included</td>
<td>Range for One feedstock: based on percentage displacement of transportation needs. Allocation method not discussed. LUC not mentioned</td>
<td>PD: GWP: 26 gm/MJ fuel EROI=11.1 (uses NREL but subtracts NG extraction)</td>
<td>gm CO₂/ MJ fuel 21-26 Saves 0-5 gm CO₂/ MJ fuel</td>
<td>1.32 (compared to 11.1 for conventional diesel)</td>
<td>H₂: 0 : 900 gal/ gal fuel or 6900 gal/ MMBTU fuel Land to displace 10, 25, 50% of transportation energy: 253M, 380M, 1.2 B acres</td>
</tr>
<tr>
<td>31 (R) 2007</td>
<td>Europe/ Finland; Vegetable Oil: NExBTL--hydrogenation Not mentioned</td>
<td>Summary of emissions testing on NExBTL 2nd generation biodiesel fuel.</td>
<td>None discussed/ LCA briefly discussed in paper • Hydrogen produced from natural gas</td>
<td>None discussed</td>
<td>Fossil diesel. 40-60% lower than fossil diesel</td>
<td>Not discussed</td>
<td>Not discussed</td>
<td>None</td>
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<td>EROI**</td>
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<td>32 (E) 2007</td>
<td>Thailand; Jatropha (JT): Trans-est. WTT Not mentioned</td>
<td>Investigated the energy consumption for 20-year investment of Jatropha Methyl Ester production in Thailand.</td>
<td>• Based on 1 ha of JT farming for 20 yr. 1100-3300 trees/ha. • Best &amp; worst case for diff. inputs. • BD factory site close to refinery; transp. in that phase not incl. • Avg BD from JT is 2.7 ton/ha/year for best case • 2-3 yr for trees to reach full yield, lasts for 20 yr. Over 20: Co-product yields; energy efficiency, and harvest yields. Allocation by energy. Direct land use impacts include preparation: plough, harrowing, and furrowing.</td>
<td>Over 20: Co-product yields; energy efficiency, and harvest yields. Allocation by energy. Direct land use impacts include preparation: plough, harrowing, and furrowing.</td>
<td>None</td>
<td>N/A</td>
<td>Range of 0.53-11.99 (Average of all cases 4.77)</td>
<td>Net energy gain= 4720 GJ/ ha</td>
</tr>
<tr>
<td>33 (F) 2007</td>
<td>Europe; Palm oil: Trans-est. WTT IFEU</td>
<td>Non-RE and GHG of palm oil cultivation, including various LUC. Comparison to conventional diesel and biodiesel for use in vehicles or power stations.</td>
<td>• Yield of both 3.5 and 4.0 tonnes palm oil/ha per year. • direct LUC of natural forest, fallow land and existing plantations of other crops like coconut and rubber.</td>
<td>Scenarios/ allocation method not discussed Cultivation of different types of land.</td>
<td>Diesel; avoided emissions are estimated. (30% avoided)</td>
<td>PME, natural forest, 7.3 t CO₂ eq/ha*; equivalent to 3.2 t CO₂ eq/ha* avoided.</td>
<td>Not discussed</td>
<td>-10 GJ/ ha<em>a, savings from conv. Diesel: 150 GJ/ ha</em>a</td>
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<tr>
<td>34 (G) 2008</td>
<td>Sweden, organic farming: Straw or short-rotation willow coppice (Salix): Gasification Not mentioned</td>
<td>Conducted 4-scenarios of either FTO or DME from two different organically grown feedstocks.</td>
<td>• Tech. feasible win 10-15 yr • 1000 ha land, 100 km transp. dist., farm trucks use fuel studied • Capital goods not incl. • Organic farming w/ 7 year rotation, N supplied by N fixing plants every 2 years. • Yield of Salix 6300kg/hayr. • Four: two feedstock; process to DME or FTD. Uses economic allocation. Direct LUC: N fertilizers and land for each feedstock which result in N₂O emissions for cases, when most land was used.</td>
<td>Conv. diesel; FTD for straw/ salix: GWP =94.0/84.9% decrease. ACP: 55.7%/ 51.2% decrease. EUP: 26.7/ 16.2% decrease.</td>
<td>Conv. diesel; FTD for straw/ salix: GWP =94.0/84.9% decrease. ACP: 55.7%/ 51.2% decrease. EUP: 26.7/ 16.2% decrease.</td>
<td>gm CO₂ eq per functional unit FT = 8.9 / 9.6 DME= 10.1/ 10.0</td>
<td>EUP (in O₂ equiv. / functional unit) FTD =9099/ 8832 DME =7728/8965 ACP FTD = 554/ 610 DME = 409 / 578 for straw/ Salix resp. FTD =£30780 DME =£32040</td>
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<td>35 (H) 2008</td>
<td>No specific location; Maize, Rapeseed, Sugar cane: Not mentioned</td>
<td>IPCC estimate of N₂O conversion from N is too low, resulting in LCA models underestimating global impacts</td>
<td>• Not a full LCA-- leaves out fossil fuel use and co-products • Conversion factor of 3-5% of newly applied N-fertilizer to N₂O, higher than IPCC factor of 1%. • Harvesting only to look at Nitrogen cycle. Nitrogen cycle specific</td>
<td>Scenarios/ allocation not included.</td>
<td>None</td>
<td>Relative warming potential of biodiesel from rapeseed is 1.0-1.7</td>
<td>Not discussed</td>
<td>None</td>
</tr>
<tr>
<td>36 (I) 2008</td>
<td>Belgium; Trans-est. WTT Simapro 7.1 &amp; Eco-Indicator 99</td>
<td>Comparison of biofuels to fossil diesel with a case-case scenario and different sensitivity analyses for allocation method and N₂O emission. WTT and WTW.</td>
<td>• Transport over 100 km for mid-size, recent car. • Data for Belgium • C-neutral • BD combustion results in a net increase in NOx.</td>
<td>Two CPA by expansion vs. none. Qualitative LUC assessment-5.5 vs 12.8 m² for 100 km transportation global impact for RME vs. Bio-ethanol respectively</td>
<td>Two: feedstock. Allocation method not discussed. Deforestation for palm in far east is discussed, but not quantitative.</td>
<td>CD (also compare to petrol and bio-ethanol) ACP and EUP combined shows 32% decrease for BD.</td>
<td>Relative results only 76% decrease from diesel</td>
<td>Relative results only</td>
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<td>37 (J) 2008</td>
<td>EU: Tallow: Trans-est. WTT Not mentioned</td>
<td>Examined the effects of tallow use—including GHG effects. 2 policy scenarios: biodiesel from tallow is 1) ineligible for support, or 2) eligible for support under EU’s RTFO.</td>
<td>• Alt. supply of biodiesel in Scen.1 is from palm oil. • Alt. supply of oleo chemicals in scen. 2 is from rendering</td>
<td>Increased emissions to 974 kg CO₂ eq/ tone tallow displaced</td>
<td>None</td>
<td>N/A</td>
<td>None</td>
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<td>38 (K) 2008</td>
<td>USA; Soybean: Trans-est. WTT and WTT LEM</td>
<td>Draft report of LEM model results and improvements, with only draft numbers.</td>
<td>LEM specific assumptions. Reported values are converted using reported density of 0.887 gm/mL and HHV of 40.37 MJ/kg. WTW for HDV with 3mpg.</td>
<td>Draft numbers only. Combination of expansion and displacement Direct cultivation. N₂O rates.</td>
<td>Diesel. (4157 gm/ mi)</td>
<td>140.82 (5361 gm/mi)</td>
<td>.949</td>
<td>Draft numbers only, but indicated 50% increase in CO₂ emissions.</td>
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<tr>
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<td>Reference Fuel</td>
<td>GWP*/ Change in GWP relative to conv. Diesel g CO&lt;sub&gt;2&lt;/sub&gt;eq/MJ</td>
<td>EROI**</td>
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<td>39 (11) 2008</td>
<td>US; Soybean: Trans-est. WTT and WTW LEM</td>
<td>Presentation on LEM model to discuss how improvements to Nitrogen cycle and climate impacts have been included.</td>
<td>• LEM specific Nitrogen cycle approach to the nitrogen cycle and climate impacts of the production. No scenarios: Combo of expansion and displacement. Direct impacts; N&lt;sub&gt;2&lt;/sub&gt;O, NO&lt;sub&gt;x&lt;/sub&gt; rates, carbon sequestration.</td>
<td>Diesel. Preliminary results only, not to be cited.</td>
<td>Diesel.</td>
<td>N/A</td>
<td>None</td>
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<td>40 (9) 2008</td>
<td>Tanzania; Clove stem: Distillation into CSO, WTW Not mentioned</td>
<td>A societal life-cycle cost (LCC) study was performed in addition to vehicle testing to determine the benefits of 25% and 50% straight CSO in diesel.</td>
<td>• Diesel Isuzu is 4cylinder, 4-stroke naturally aspirated DI engine. No CSO is used directly as a fuel.</td>
<td>Pure diesel, and blends of diesel with straight CSO (no processing to biodiesel)</td>
<td>50% blend results in 7% increase in total emissions; the 25% blend results in 1% decrease.</td>
<td>CSO is more expensive</td>
<td>None</td>
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<td>41 (E,G) 2008</td>
<td>Argentina; Soybean: Trans-est. WTT Ecoinvent</td>
<td>Abstract from report submitted to Int. J. LCA for biodiesel from soy in Argentina with regional specificities.</td>
<td>Argentinean regional specificities—not defined.</td>
<td>One using economic allocation method. Cultivation of land use is included.</td>
<td>Fossil low-sulfur diesel in CH</td>
<td>WTT: 48.9</td>
<td>WTT: 2.29</td>
<td>None</td>
</tr>
<tr>
<td>42 (E,G,R) 2008</td>
<td>France; Rape and Sunflower: Trans-est. WTT and WTW TEAM database</td>
<td>Comparison of biofuels to fossil diesel with a base-case scenario and different sensitivity analyses for allocation method and N&lt;sub&gt;2&lt;/sub&gt;O emission. WTT and WTW LCA.</td>
<td>• Carbon neutral principle-WTT=WTT + No land use change • WTW analysis w/ Belingo Vehicle on normalized European driving cycle (NEDC)</td>
<td>Two: Type of feedstock with expanded allocation. Direct land use— considers fertilizers and direct ag inputs. No indirect changes.</td>
<td>Diesel (with comparisons for EOH and gasoline also)</td>
<td>WTT Rape: 12 Sunflower: 18 Domestic: 35.8 Imported: 15.4 &amp; 1.1% reduction in 2004 emissions levels.</td>
<td>None</td>
<td></td>
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<td>43 (G,R) 2008</td>
<td>Italy; 80% Rapeseed &amp; 20% Sunflower: Trans-est. WTT Not mentioned</td>
<td>An integrated assessment for large-scale biodiesel production for Italy to meet EU Directive goals of 3.2MT biodiesel in 2010.</td>
<td>Linear trend in oil demand to 2010 imported BD is from Hungary • Oilseeds: cultivated in abandoned lands; will not replace food crops; replace fodder plants and cereals; from ear-marked crops; are cultivated with intensive ag methods • All BD prod is exempt from taxes</td>
<td>Two: origin of feedstock with expanded allocation. Direct land requirement for growing crop is considered.</td>
<td>Fossil Diesel, 1.1% reduction in 2004 emissions levels.</td>
<td>For WTT: Rape ~ 3.3 Sunflower ~2.7 Domestic: 3.2 MT biodiesel req’d to displace 5.75% total energy demand in 2010, 3.7 Mt ha req’d, (26% of ag land) Economic: 4.8% loss of total energy taxes and 0.3% loss of total revenues.</td>
<td>None</td>
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<td>44 (E,G,R) 2008</td>
<td>Canada and USA; Soybean and Canola: Trans-est. WTT and WTW GREET and GHGenius</td>
<td>Comparison of biodiesel pathways in GREET 1.8 and GHGenius 3.12 in 2007. Comparison limited to data easily extracted from GREET. Second comparison of results from different feedstocks in GHGenius</td>
<td>• Year 2007, 2002 US scenarios • Results on a HHV basis. GHGenius includes energy required to manufacture farm equipment. GREET does not. • Different land-use calculation in each Sensitivity analysis of paper incl. of different oil extraction methods, co-product allocation. Does not use zero combustion emissions</td>
<td>1 for GHGenius vs. GREET. GHGenius test: Two F/S, with sensitivity analysis • GHGenius: CPA combo of expansion and displacement: GREET allocation selection. GREET: emissions calculated for N&lt;sub&gt;2&lt;/sub&gt;O from applied N. GHGenius incl. N&lt;sub&gt;2&lt;/sub&gt;O created when seed N is fixed. Discussion on potential effects of ILUC. Comparison of two different model results, and compare to fossil diesel.</td>
<td>Diesel. After Combustion (88.7-89.7) Soy: 60-71% Canola: 75-78% EROI: 4.2984</td>
<td>Uses 2.5 from Bernesson et al. 2004 for analysis</td>
<td>None</td>
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<td>45 (E,G,R) 2008</td>
<td>Average European. Rapeseed (RSO), Palm Oil (PO), Tallow: Ecofining GD SimaPro data w/ data for UOP processes.</td>
<td>Description of UOP EcoFining process for Green Diesel (GD) production and compares ER and GWP of GD to bio-, petroleum and syn-diesel.</td>
<td>• GHG contributions from N₂O, CO₂, and CH₄. • Combustion emissions are not incl (GD: CO₂ only from renewable oils, no offsets; BD: only MeOH-derived CO₂ of fossil origin). • Farming rapeseed and palm. Tallow is waste from meat plants. Only emissions for transport</td>
<td>4 scenarios for BD, 4 for GD—different feedstock and if biogas (BG) is used as a fuel. No CPA for palm oil. Expanded allocation for rapeseed meal. Energy and Economic for tallow. N₂O emissions are included, but no sensitivity to them. LUC out of scope.</td>
<td>GD compared to biodiesel from transesterification and to low sulfur petroleum. ER= .787 GWP= 84</td>
<td>Biodiesel: RSO: 46 PO: 54 PO w. BG: 31 Tallow: 20 GD: RSO: 41 PO: 48 P O w. BG: 26 Tallow: 5</td>
<td>Biodiesel: RSO: 2.4 PO: 2.4 PO w. BG: 2.5 Tallow: 4.2 GD: RSO:2.4 PO:2.7 P O w. BG: 2.9 Tallow: 9.1</td>
<td>1. GHG contributions from N₂O, CO₂, and CH₄. 2. Combustion emissions are not incl (GD: CO₂ only from renewable oils, no offsets; BD: only MeOH-derived CO₂ of fossil origin). 3. Farming rapeseed and palm. Tallow is waste from meat plants. Only emissions for transport</td>
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<tr>
<td>46 (E,G,R) 2008</td>
<td>US/ Canada Soy-oil: WTW 1. Trans-est. and hydrogenation (2. SuperCetane and 3. GreenDiesel from Ecofining) GREET (and ASPEN plus)</td>
<td>GREET model for biodiesel and different scenarios of renewable diesel from soy oil with different scenarios for allocation procedures.</td>
<td>• Boundaries incl. farming activities, transp., oil extraction, fuel prod., and use. • N₂O and other emissions factors based on IPCC 2006 estimates. • Detailed description of fertilizer use and rates Energy reported is fossil energy. Total energy also included in study.</td>
<td>12 scenarios for 3 production methods and 4 co-product allocation. Co-prod methods: 1. Displacement 2. by Energy 3. by mkt. value 4. hybrid of displacement and allocation. No potential LUC is considered. Only emissions rates from direct cultivation.</td>
<td>Low Sulfur Diesel. ER= .826 GWP = 95 GWP Biodiesel: 66-94% RDI- 62-130% RDII- 66-74%</td>
<td>Biodiesel 1) 5, 2)30, 3) 32, 4) 5 SuperCetane 1)-30 2) 32 3) 36 4) -20 Ecofining 1) 30, 2) 24, 3)25, 4) 32</td>
<td>Biodiesel: 1) 5.2, 2) 2.5, 3) 2.4, 4)5.2 RDI-SuperCetane 1) 8.3 , 2) 2.6, 3)2.2, 4) 2.2 RDII-Ecofining. 1)1.8, 2)2.9, 3)2.8, 4) 1.7</td>
<td>1. Boundaries incl. farming activities, transp., oil extraction, fuel prod., and use. 2. N₂O and other emissions factors based on IPCC 2006 estimates. 3. Detailed description of fertilizer use and rates Energy reported is fossil energy. Total energy also included in study.</td>
</tr>
<tr>
<td>47 (E,G,R) 2008</td>
<td>China Soy-oil. WTW. Trans- esterification. Variety of data in Excel model</td>
<td>LCA of avg Chinese conditions to determine relative benefit of energy, emissions and cost of soy-BD to CD. Results: BD has 76% lower fossil energy use and lower HC, CO, PM, Sox and CO₂ emissions, its cost (86% higher than CD) will limit implementation in China.</td>
<td>Data is from on-site data, literature values, statistics and the GREET model based on Average Chinese conditions. Emissions not converted to CO₂ eq. (estimated with NOx emissions at 296)</td>
<td>Conv. diesel CO₂ = 91.4 (CO₂ eq ~ 201) ER= .796</td>
<td>CO₂ emissions =29.7 (67% lower) (CO₂ eq ~ 226)</td>
<td>4.63 (Prueksakorn) 6.25 (Tobin, 2005)</td>
<td>Human health is of concern since JCL is highly toxic.</td>
<td>1. Data is from on-site data, literature values, statistics and the GREET model based on Average Chinese conditions. 2. Emissions not converted to CO₂ eq. (estimated with NOx emissions at 296)</td>
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<tr>
<td>48 (E) 2008</td>
<td>Jatropha (JCL) Trans- esterification Overview of lit</td>
<td>Gives an overview of available info on different process steps of Jatropha (JCL). Includes review of 2 JCL-LCA studies The available info for JCL is limited, making it difficult to assess if the fuel produced will have a lower negative EI. Results from two JCL-LCA studies are discussed and compared. One paper is Prueksakorn, 2006 (already incl.)</td>
<td>Allocation is included in other studies, but method of each is not discussed. LUC is discussed, but results not incl. in other studies.</td>
<td>Conv. Diesel and RME. ER= .793</td>
<td>Incl. in other papers, but numbers not discussed.</td>
<td>4.63 (Prueksakorn) 6.25 (Tobin, 2005)</td>
<td>Human health is of concern since JCL is highly toxic.</td>
<td>1. Gives an overview of available info on different process steps of Jatropha (JCL). Includes review of 2 JCL-LCA studies The available info for JCL is limited, making it difficult to assess if the fuel produced will have a lower negative EI. Results from two JCL-LCA studies are discussed and compared. One paper is Prueksakorn, 2006 (already incl.)</td>
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<td>49 (E,G,R) [53] 2008</td>
<td>India; Jatropha Oil; Transesterification; WTW GHG emissions and energy use; EcoInvent 2.0 Module.</td>
<td>A relatively comprehensive evaluation of GHG emissions in the life cycle of Jatropha-BD produced in India, and comparison with CD. The study has shown, w.o. iLUC, Jatropha oil-based BD contributes to the reduction of GHG emissions.</td>
<td>Assumes a 20 year system lifetime (Infrastructure building is not included in the LCA). Yield is 2.38 tonnes /ha/year with oil content of 35% by wt. No irrigations after first 3 years. No pesticides and herbicides. Lifetime (after oil extraction) is converted to process energy use in the biodiesel plant.</td>
<td>LUC not incl. Sensitivity analyses include 15 parameters including yield of Jatropha seeds, fuel use during Jatropha production, oil contents, offset for using seed cake as fertilizer, irrigation, and etc. LCA results appear sensitive to variations in these parameters.</td>
<td>Petroleum diesel.</td>
<td>WTW GHG emissions 5.1 g CO₂e (gross tonne kilometer (GTK) for B100 (neat biodiesel)); 62% less emissions than petroleum diesel</td>
<td>Energy ratio is 1.9 for B100.</td>
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<td>50 (E,G,R) [53] 2008</td>
<td>US; Tallow; Hydrogenation co-feeding process; WTW GHG emissions and energy use.</td>
<td>A full LCA of energy use and GHG emissions for tallow RD from the production of animal feed, cattle growth in the feedlot, meat processing and rendering, to the refining of tallow into renewable diesel fuel. The study indicated tallow RD contributes to significant GHG emissions reduction.</td>
<td>Feed is corn and soybean meal at a 3 to 1 wt. ratio. Feed: animal weight gain is 6 to 1. Avg animal is raised from 600 to 1200lbs before sent to meat processing - it produces 140 lbs tallow. CPA of beef, hide, and animal feed, and propane produced during tallow hydrogenation.</td>
<td>Sensitivity analysis incl.: fertilizer application rates, animal feed production, fuel use in feed production, the feed to weight gain ratio, and the transport distance for cattle. CPA by mass, energy, and market values.</td>
<td>Petroleum diesel</td>
<td>GWP = 88</td>
<td>Total GHG emission for tallow renewable diesel is 11-18 gCO₂e/MJ fuel; 80-88% less GHG emissions than petroleum diesel</td>
<td>Energy ratio ranges from 4.5 to 7.1 depending on the selected co-product allocation method.</td>
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<tr>
<td>51 (E,G) [54] 2008</td>
<td>European; Palm oil, rapeseed oil, and animal waste; hydrogenation stand alone process; WTW energy use and GHG emissions.</td>
<td>LCA of hydrogenated bio-based oils/fats. Boundary for palm and rapeseed incl. F/S production, oil extraction, oil refining into diesel fuel, and all transportation steps. For animal waste (tallow, chicken fats, and other triglyceride-based materials), energy inputs and emissions during the upstream biomass production are not incl.</td>
<td>Feed is corn and soybean meal at a 3 to 1 wt. ratio. Feed: animal weight gain is 6 to 1. Avg animal is raised from 600 to 1200lbs before sent to meat processing - it produces 140 lbs tallow. CPA of beef, hide, and animal feed, and propane produced during tallow hydrogenation.</td>
<td>Sensitivity analysis incl.: fertilizer application rates, animal feed production, fuel use in feed production, the feed to weight gain ratio, and the transport distance for cattle. CPA by mass, energy, and market values.</td>
<td>Petroleum diesel</td>
<td>GWP = 88</td>
<td>Total GHG emission for tallow renewable diesel is 11-18 gCO₂e/MJ fuel; 80-88% less GHG emissions than petroleum diesel</td>
<td>Energy ratio ranges from 4.5 to 7.1 depending on the selected co-product allocation method.</td>
</tr>
<tr>
<td>52 (E,G,R) [55] 2009</td>
<td>U.S. (CA) Soyoil, WTT and TTW. Trans-esterification Ca-GREET</td>
<td>CA-GREET soy-BD pathway. Provides numbers for LCFS policy support.. ILUC is incl. in GTAP model, adding GWP factor to final number from CA-GREET.</td>
<td>Soybeans grown in Midwest, shipped to CA and WA for B100 production. Used in CA in HDDV.</td>
<td>Allocation by energy (different energy ratios for each step) N factors considered. ILUC addressed in GTAP model.</td>
<td>None (but ULSD from other report: GWP: 94.71 ER: .785) (&amp; RD below)</td>
<td>26.93 (+42.0 for ILUC)</td>
<td>0.736 (total- incl. C in plant) 2.754 (fossil—no plant C)</td>
<td>Indirect LUC is estimated to add 42.0 gCO₂ eq / MJ fuel to final number!</td>
</tr>
<tr>
<td>53 (E,G,R) [55] 2009</td>
<td>U.S. (CA) Soyoil, WTT and TTW. Hydrogenation Ca-GREET</td>
<td>CA-GREET soy- RD pathway. Provides numbers for LCFS policy support.</td>
<td>Soy from Midwest—shipped to CA and WA for BD prod. RD is assumed to be RDII, with similar process to Nest Oil. Used in CA in HDDV.</td>
<td>Allocation by energy (different energy ratios for each step) N factors considered. ILUC not included.</td>
<td>None (but ULSD from other report: GWP: 94.71 ER: .785) (&amp; B100 above)</td>
<td>28.02</td>
<td>0.739 (total- incl. C in plant) 2.83 (fossil—no plant C)</td>
<td>No number for ILUC is addressed.</td>
</tr>
<tr>
<td>Study No; Ref No.; Year</td>
<td>Location; Feedstock; Production Pathway; LCA tool used</td>
<td>Summary of Paper</td>
<td>Critical Assumptions</td>
<td>No. of Scenarios Method of Co-Product Allocation and LUC considerations</td>
<td>Reference Fuel</td>
<td>GWP*/ Change in GWP relative to conv. Diesel g CO₂e/MJ</td>
<td>EROI**</td>
<td>Other considerations***</td>
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<td>54 (E,G,R) (M₃) 2009</td>
<td>No location Soy &amp; rapeseed Hydrogenation/ UOP Ecofining SimaPro 7.0 and data from lit and UOP.</td>
<td>Compares assumptions and approaches from different models (DOE, CONCAWE, PNAS) DOE (no N₂O emissions) produces most favorable GWP results. Energy inputs are lower for soy than rapeseed</td>
<td>Ranges of assumptions from different models. DOE (SOY,CPA by mass, no N₂O emissions) CONCAWE (rapeseed, displacement), Academy of Science (soy, mass allocation)</td>
<td>Mass allocation Fertilizer emission factors, no direct.</td>
<td>Conv diesel: GWP 85.9</td>
<td>SBO/BD: 23.6-48.9 SBO/GD: 17.3-48.8 RSO/BD: 52.6 RSO/ GD: 41.0</td>
<td>SBO/BD: 2.77-3.03 SBO/ GD: 2.94- 3.57 RSO/ BD: 1.78 RSO/ GD: 3.03</td>
<td>None</td>
</tr>
<tr>
<td>55 (E,G) (M₃) 2009</td>
<td>Taiwan, Soy and Rapeseed. Transest. Not mentioned</td>
<td>LCA for biofuels in Taiwan, incl. ethanol and BD from rapeseed &amp; soy. Doesn't delineate b/w FE and non-FE, resulting in disbenefit for soy BD.</td>
<td>Based on 1 ha/yr of farmland (harvest for soy, rape is 2.35 and 2.25 tonnes, which produce 476 and 1012 L, resp.). Energy is 9500 kcal/ L</td>
<td>None discussed</td>
<td>None—referenced to other papers.</td>
<td>Soy: (1478.4 kg/ ha) = 78.1 gm/MJ Rapeseed (2954.1 kg/ha) = 73.4 gm/MJ</td>
<td>Soy = .99 Rape= 1.83 Total energy</td>
<td>None.</td>
</tr>
</tbody>
</table>

E Reference included in Figure 1- Energy Return Chart
G Reference included in Figure 2 on global warming potential
R Reference included in Figure 3 on relative GWP benefit to conventional fuel.
**Bold** indicates critical reference included in discussion of (E) energy section and/ or (G) global warming potential section.
REFERENCES


