

Biodistillate Transportation Fuels 3 – Life Cycle Impacts

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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.^(1,2,3,4,5) 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⁽⁶⁾) 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,^(7,8) 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 “attributorial” or “consequential” depending on the inclusion of indirect effects.^(9,10)

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.^(11,12) The survey excluded LCA studies strictly related to ethanol. 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,⁽¹³⁾ 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 fuels’ production and use—starting with the raw material and ending with fuel consumption.⁽¹⁴⁾ 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.⁽¹⁵⁾) 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 recognizably flawed and is being reviewed, especially as land use changes become more influential in the overall environmental impacts.⁽¹⁶⁾ 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.^(17,18,19,20,21) 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.⁽¹⁷⁾

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.^(18,19) 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, LCI, iFEST 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.⁽¹⁷⁾ 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))

Model	Biodiesel Pathways	Region	Publicly Available	Notes
BEES	None	US and EU data	Yes	Adapted for bio-based products
BESS	None	US	Yes	Specific for corn-to-ethanol
EBAMM	None	US data	Yes	Excel model uses data from 9 studies and outcomes from each dataset
EIO-LCA	None	US and EU data	Yes	
GaBi	None	EU Germany	Yes - \$\$	Can model ethanol
GEMIS	forest residue	EU data	Yes	Limited pathways.
GHGenius	soybeans, canola, palm, tallow, yellow grease and marine oils.	US and Canadian data	Yes	200 pathways. Used in Canadian policy making.
GREET	Soybeans	US data	Yes	100 pathways, used in US policy.
LBST E3 Database	Soybeans and rapeseed	EU data	No	Petroleum and bio-based fuel pathways, used by European Commission's Joint Research Centre
LEM	Soybeans	US data	No	Basis of GHGenius.
SimaPro	None	EU and US data	Yes - \$\$	Has biodiesel processes, but no pathways.

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.⁽²⁷⁾ Fargione et al.⁽²⁸⁾ and Crutzen et al.⁽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.⁽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).^(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 N₂O emissions.⁽²⁹⁾ The IPCC consensus is that N₂O has a GWP 296 times that of CO₂, so small changes in N₂O can result in significant differences in GWP.⁽³⁰⁾ Therefore, it is crucial to account for all N inputs and outputs from cultivation of land to grow biomass -- including crop residues, fertilizer, N fixation, manure, deposition, gaseous losses, crop output, runoff, N transfer between co-rotated crops, and others. It is also important to know how these factors change over time.⁽³¹⁾ Variations in assumptions about N₂O 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 N₂O conversion factor for LCA modeling to estimate the amount of N₂O 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⁽²⁶⁾ and the GHGenius model uses a factor of 1.125%.⁽¹⁷⁾ Using these relatively low conversion factors generally results in GWP benefits for biodiesel pathways relative to conventional diesel. However, Crutzen et al.⁽²⁹⁾ concluded that the IPCC emission factor for N₂O was seriously underestimated, and recommended a conversion value equivalent to an IPCC factor of 2.24-3.74.⁽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 N₂O impacts.^(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.⁽²³⁾ Expansion of croplands may require reducing forest lands or other fallow lands elsewhere, which could result in extremely large releases of CO₂ 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.⁽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.⁽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).⁽³⁴⁾

LCA models that include indirect effects have been defined recently as "consequential" LCA (CLCA).⁽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.⁽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^{(37,38,39):}



Documents

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- ♦ **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. Bernesson, 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.

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 of data points – see for example the three results shown for Study No. 6 in the year 2003. Also note that different symbol shapes are used to distinguish biodiesel from renewable diesel, and different colors represent different feedstocks.

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.⁽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.

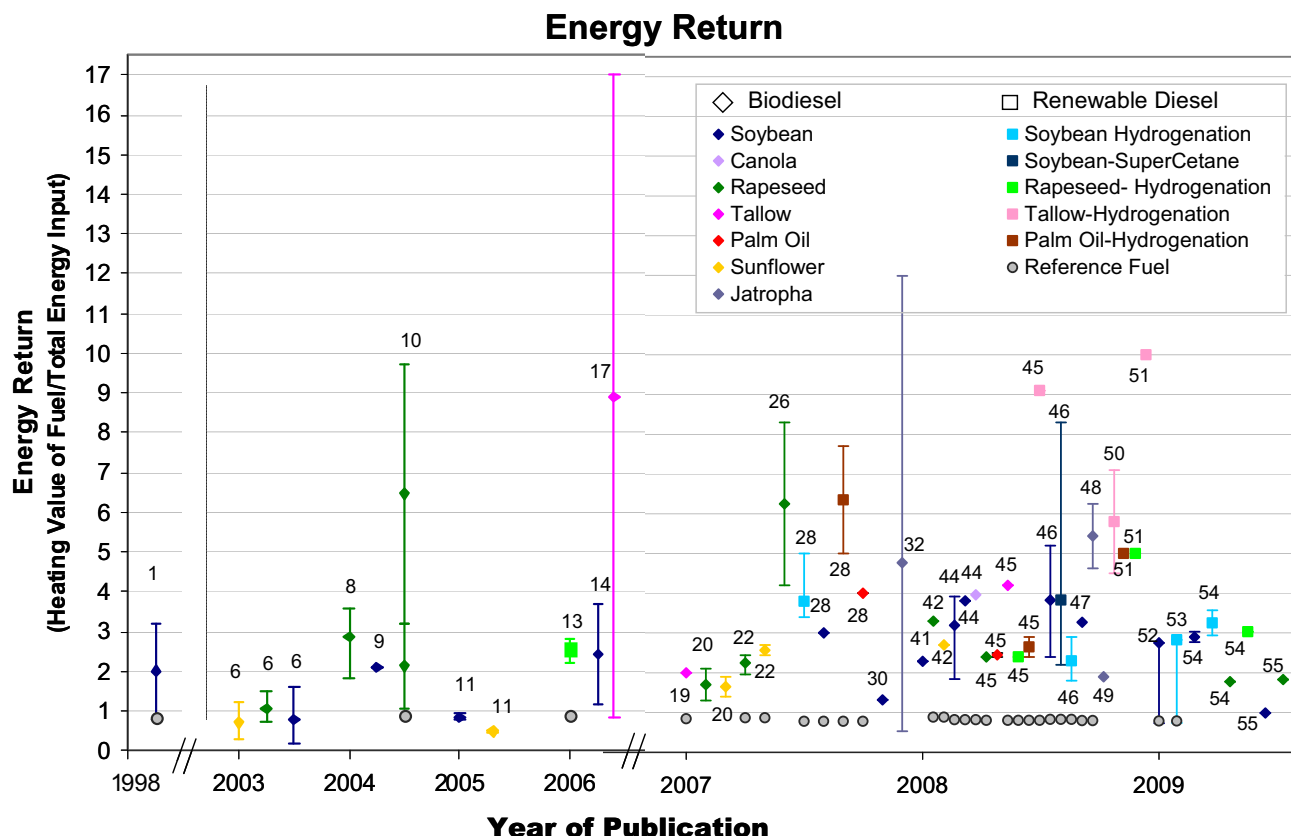


Figure 1: Energy return values from 30 different biodistillate references.

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,⁽⁴⁷⁾ Cocco,⁽⁴⁸⁾ Edwards,⁽²¹⁾ and Prieur,⁽⁴⁹⁾ 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.⁽²⁵⁾ 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⁽⁴⁷⁾) 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⁽³⁷⁾) 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⁽¹⁴⁾) 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.⁽⁵⁰⁾) 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 conventional diesel. Other studies related to NExBTL production are Study No. 31 (which is not included in the ER Figure 1⁽⁵¹⁾) and study No. 53⁽⁵²⁾, which supports CARB's LCFS and will be discussed later in more detail.

Study No. 22 (Edwards et al.⁽²¹⁾) 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.⁽¹⁷⁾ 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⁽⁴³⁾ 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⁽³⁶⁾ and Study No. 45.⁽⁴⁰⁾ 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⁽⁵³⁾ (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⁽⁴¹⁾ 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 N₂O 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 hydroprocessing 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 CO₂ 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 2. IPCC GHG Equivalency Factors

Greenhouse Gas	tCO ₂ eq/ t
CO ₂	1
Methane (CH ₄)	23
Nitrous Oxide (N ₂ O)	296
CFC-12	10,600
HFC-134a	1,300
O ₃	6

The studies shown in Fig. 2 reported GWP as g CO₂ 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 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 CO₂ eq. per MJ of fuel produced. The range of conventional diesel GWP values reported in these studies is from 22 to 240 grams of CO₂ 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.⁽³³⁾ Delucchi's results demonstrate the potentially severe impacts of N₂O 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 CO₂ 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).